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AN INVESTIGATION OF THE USE OF  
THE HOT-WIRE ANEMOMETER IN NON-ISOTHERMAL  
AIR FLOW

A Thesis

Submitted to the Faculty

of

Purdue University

by

Edwin George Wiggins

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

in

Nuclear Engineering

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## NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Dimensions</u>
A	Empirical constant	
a	Empirical constant	volts/ $^{\circ}\text{F}$
B	Empirical constant	
C	Defined by Equation 17	$\left(\frac{\text{volts}}{\text{ohms}}\right)^2 \left(\frac{\text{ft}}{\text{sec}}\right)^{\frac{1}{2}}$
$C_p$	Specific heat of air	BTU/lb $^{\circ}\text{F}$
D	Diameter of hot-wire	inch
E	Instantaneous hot-wire/thermocouple voltage	volts
$\bar{E}$	D.C. component of hot-wire/thermocouple voltage	volts
$\bar{E}_0$	Thermocouple reference voltage	volts
$e'$	Fluctuating component of hot wire/thermocouple voltage	millivolts
h	Convective heat transfer coefficient	BTU/hr $\cdot$ ft $^2 \cdot ^{\circ}\text{F}$
k	Thermal conductivity of air	BTU/hr $\cdot$ ft $\cdot ^{\circ}\text{F}$
$\bar{k}$	Time average thermal conductivity of air	BTU/hr $\cdot$ ft $\cdot ^{\circ}\text{F}$
$k'$	Fluctuating component of thermal conductivity of air	BTU/hr $\cdot$ ft $\cdot ^{\circ}\text{F}$
$\ell$	Length of hot wire	inch
m	Empirical constant	
Nu	Nusselt number	
$\Delta P$	Pressure difference between points upstream and downstream of orifice plate	inches of manometer fluid
Pr	Prandtl Number of air	
$q''$	Heat flux from surface of hot-wire	BTU/hr $\cdot$ ft $^2$



$R$	Pipe radius	inch
$r$	Distance from pipe centerline	inch
$R_a$	Hot-wire resistance at local air temperature	ohm
$\bar{R}_a$	Hot-wire resistance at time average local air temperature	ohm
$R_o$	Hot-wire reference resistance	ohm
$R_w$	Hot-wire resistance at operating temperature	ohm
$r'_a$	Fluctuating hot-wire resistance corresponding to fluctuating component of local air temperature	ohm
$Re$	Reynolds Number	
$S_u$	Hot-wire sensitivity to velocity fluctuations	millivolts/ft/sec
$S_T$	Hot-wire sensitivity to temperature fluctuations	millivolts/ $^{\circ}F$
$T, T_a$	Instantaneous local air temperature	$^{\circ}F$
$T, \bar{T}_a$	Time average local air temperature	$^{\circ}F$
$T_c$	Time average temperature at pipe centerline	$^{\circ}F$
$T_o$	Wall temperature	$^{\circ}F$
$T_w$	Wire temperature	$^{\circ}F$
$t'$	Fluctuating component of local air temperature	$^{\circ}F$
$u$	Instantaneous local flow velocity	ft/sec
$\bar{u}$	Time average local flow velocity	ft/sec
$u'$	Fluctuating component of local flow velocity	ft/sec
$\alpha$	Hot-wire resistivity coefficient	$^{\circ}F^{-1}$
$\rho$	Instantaneous air density	lb/ft <sup>3</sup>
$\bar{\rho}$	Time average air density	lb/ft <sup>3</sup>
$\rho'$	Fluctuating component of air density	lb/ft <sup>3</sup>



## ABSTRACT

Wiggins, Edwin George, M.S. in Nuclear Engineering, Purdue University, January 1969. An Investigation of the Use of the Hot-Wire Anemometer in Non-Isothermal Air Flow. Major Professor: Alexander Sesonske.

Procedures were developed for the calibration of the hot-wire anemometer in a non-isothermal flow. Various methods of using the results of calibration to compute turbulent fluctuations of velocity and temperature were considered, and the Arya and Plate modification of the Kovaszny Fluctuation Diagram method was found to give the most accurate results. The method requires independent measurement of the temperature fluctuations which was obtained with a rapid response thermocouple.

The calculated values of velocity turbulence intensity show deviations of 36 percent from the results of Laufer; however, this deviation is to be expected in view of the estimated experimental error. These errors were probably caused by contamination of the wire during the lengthy calibration process.

All measurements were made in air flowing in a 1.0625 inch diameter pipe at Reynolds Numbers between 30,000 and 50,000. A heat input of 430 watts over the last 58 inches before the probe was used to generate temperature differences between wall and centerline of 48 to 63°F at the probe location.

The procedures developed and the experimental problems identified are the contribution of this investigation to a comprehensive research program of non-isothermal hot-wire measurements in fluids of a wide range of Prandtl Numbers.









## INTRODUCTION

The hot-wire anemometer has been used extensively for the measurement of velocity fluctuations in isothermal flow of gases. The principles and procedures involved are discussed by Kovasznay<sup>1,2</sup> and by Kronauer<sup>3</sup>.

Corrsin<sup>4</sup> has shown that in addition, the hot-wire anemometer has the potential to measure simultaneous velocity and temperature fluctuations in non-isothermal flow. Experimental work of this nature has been done by Corrsin and Uberoi<sup>5</sup>, Gibson Chen and Lin<sup>6</sup>, Deissler<sup>7</sup>, Kunstman<sup>8</sup>, and Arya and Plate<sup>9</sup>. The present work was concerned with the development of experimental procedures and the identification of problems associated with making of such measurements in a non-isothermal air flow.

In isothermal flow the only flow variable affecting the anemometer output is the velocity. Thus the anemometer voltage fluctuation is directly proportional to the velocity fluctuation and the anemometer steady voltage is directly proportional to the mean velocity.

In non-isothermal flow, however, both the velocity and ambient temperature fluctuations affect the anemometer output. Considerable difficulty has been encountered by previous workers in separating the two effects. Errors up to 750 percent<sup>8</sup> have been reported in non-isothermal measurements, while in isothermal measurements 10 percent error or less is expected.

The non-isothermal flow measurements of the present work were preceded by velocity fluctuation measurements in isothermal flow with a



hot-wire paralleling the work of Laufer<sup>10</sup> and Sandborn<sup>11</sup> and temperature fluctuation measurements in non-isothermal flow with a rapid response thermocouple. Thus the velocity and temperature fluctuation intensities measured with the hot-wire in non-isothermal flow could be compared with results of more direct measurements.



## THEORETICAL BACKGROUND

The constant temperature hot-wire anemometer consists of a fine tungsten or platinum wire maintained by a feedback system at some constant temperature above that of the fluid in which it is inserted. The convective heat loss from the wire is balanced by joulean heating of the wire by the current supplied by the feedback system.

King<sup>12</sup> solved the convection problem by assuming potential flow around the wire and obtained the following relationship:

$$Nu = (A + BRe^{\frac{1}{2}}) \left( 1 + \frac{1}{2} \frac{T_w - T_a}{T_a} \right)^m,$$

where  $Re = \frac{Du\rho}{\mu}$ .

Although it is recognized that King's assumptions are unacceptable, the functional form of his relationship has proved to be a satisfactory representation of experimental data. Thus it is seen that the joulean heating current (or voltage) required to maintain the wire at a constant temperature is a function of the instantaneous velocity of the flow and the difference in temperature between wire and fluid.

In isothermal flow, the temperature difference is constant and the system can be used to measure the mean and fluctuating components of the instantaneous velocity. In non-isothermal flow the fluid temperature has a fluctuating component that affects the heat transfer in addition to the effect of the fluctuating component of the velocity. Thus in





principle, the system can be used to measure velocity and temperature fluctuations, since it is sensitive to both fluctuations.

#### Hot-Wire in Isothermal Flow

The following parallels Corrsin's<sup>4</sup> treatment for a constant current hot-wire anemometer. For heat transfer to flow over a cylinder:

$$Nu = (A + B Re^{1/2}) \left[ 1 + \frac{1}{2} \frac{T_w - T_a}{T_a} \right]^m. \quad (1)$$

In the range of interest,

$$\frac{1}{2} \frac{T_w - T_a}{T_a} \ll 1. \quad (2)$$

Thus Equation 1 may be simplified to

$$Nu = A + B Re^{1/2}. \quad (3)$$

By definition,

$$Nu = \frac{hD}{k} = \frac{q''D}{k(T_w - T_a)}. \quad (4)$$

For electrical resistance heating,

$$q'' = \frac{E^2}{R_w \pi D \ell}. \quad (5)$$

Substitution of Equations 4 and 5 into 3 yields

$$\frac{E^2}{R_w (T_w - T_a)} = (\pi k \ell A) + (\pi k \ell B) Re^{1/2} \quad (6)$$

By definition,

$$Re = \frac{\rho u D}{\mu}. \quad (7)$$



Thus,

$$\frac{E^2}{R_w(T_w - T_a)} = (\pi k \ell A) + (\pi k \ell B \left[ \frac{\rho D}{\mu} \right]^{1/2}) u^{1/2}. \quad (8)$$

The quantities in parentheses on the right side of Equation 8 are constants. For constant temperature operation of the hot-wire in an isothermal flow the following mean and deviation quantities are used:

$$u = \bar{u} + u' \quad \text{and} \quad E = \bar{E} + e'. \quad (9)$$

Substitution of Equations 9 into Equation 8 yields, after small terms have been discarded,

$$\frac{\bar{E}^2 + 2\bar{E}e'}{R_w(T_w - T_a)} = (\pi k \ell A) + (\pi k \ell B \left[ \frac{\rho D}{\mu} \right]^{1/2}) \bar{u}^{1/2} \left(1 + \frac{u'}{\bar{u}}\right)^{1/2} \quad (10)$$

By definition,

$$T_w - T_a = \frac{1}{\alpha R_o} (R_w - R_a). \quad (11)$$

According to the binomial theorem

$$\left(1 + \frac{u'}{\bar{u}}\right)^{1/2} = 1 + \frac{1}{2} \frac{u'}{\bar{u}} + \dots \quad (12)$$

Since  $\frac{u'}{\bar{u}} \ll 1$ , it is assumed that higher order terms may be neglected in Equation 12. Thus Equation 10 becomes

$$\frac{\bar{E}^2}{R_w(R_w - R_a)} + \frac{2\bar{E}e'}{R_w(R_w - R_a)} = \left(\frac{\pi k \ell}{\alpha R_o} A\right) + \left(\frac{\pi k \ell}{\alpha R_o} B \left[\frac{\rho D}{\mu}\right]^{1/2}\right) (\bar{u}^{1/2} + \frac{u'}{2\bar{u}^{1/2}}). \quad (13)$$

Time averaging of Equation 13 yields

$$\frac{\bar{E}^2}{R_w(R_w - R_a)} = \left(\frac{\pi k \ell}{\alpha R_o} A\right) + \left(\frac{\pi k \ell}{\alpha R_o} B \left[\frac{\rho D}{\mu}\right]^{1/2}\right) \bar{u}^{1/2}. \quad (14)$$



Subtraction of Equation 14 from 13 gives

$$\frac{2\overline{E}e'}{R_w(R_w - R_a)} = \left( \frac{\pi k \ell}{\alpha R_o} B \left[ \frac{\rho D}{\mu} \right]^{1/2} \right) \frac{u'}{2\overline{u}^{1/2}}, \quad (15)$$

or

$$\frac{4\overline{E}e'}{R_w(R_w - R_a) \overline{Cu}^{1/2}} = \frac{u'}{\overline{u}}. \quad (16)$$

Note that

$$C = \frac{\pi k \ell}{\alpha R_o} B \left[ \frac{\rho D}{\mu} \right]^{1/2}, \quad (17)$$

and that this same quantity appears as the coefficient of  $\overline{u}^{1/2}$  in Equation 14. Squaring, time averaging, and taking the square root of Equation 16 yields

$$\frac{4\overline{E} \sqrt{\overline{e'^2}}}{R_w(R_w - R_a) \overline{Cu}^{1/2}} = \frac{\sqrt{\overline{u'^2}}}{\overline{u}} \quad (18)$$

#### Rapid Response Thermocouple in Non-Isothermal Flow

The behavior of a thermocouple over a fairly large range of temperature may be expressed as

$$E = E_o + aT. \quad (19)$$

The following fluctuating quantities are introduced:

$$E = \overline{E} + e' \quad \text{and} \quad T = \overline{T} + t'. \quad (20)$$

Substitution of Equations 20 into 19 yields

$$\overline{E} + e' = E_o + a(\overline{T} + t'). \quad (21)$$



Time averaging of Equation 21 yields

$$\bar{E} = E_o + a\bar{T} \quad . \quad (22)$$

Subtracting Equation 22 from 21 yields

$$e' = at' \quad (23)$$

Squaring, time averaging, and taking the square root of Equation 23

$$\text{gives } \overline{\sqrt{e'^2}} = a\sqrt{\overline{t'^2}} \quad . \quad (24)$$

#### Hot-Wire in Non-Isothermal Flow

The following parallels Corrsin's<sup>4</sup> treatment for a constant current hot wire anemometer.

Equation 8 is still valid, however,  $\rho$  and  $k$  are no longer constants.

Substitution of Equation 11 into 8 yields

$$\frac{E^2}{R_w(R_w - R_a)} = \left(\frac{\pi \ell}{\alpha R_o} A\right) k + \left(\frac{\pi \ell D^{1/2}}{\alpha R_o}\right) \cdot \left[\frac{k}{C_p \mu}\right]^{1/2} B \rho^{1/2} u^{1/2} k^{1/2} C_p^{1/2} \quad . \quad (25)$$

It is assumed that

$$\frac{k}{C_p \mu} = \frac{1}{Pr}$$

is constant, and that  $C_p$  itself is also constant.

The following mean and deviation quantities are considered:

$$\begin{aligned} R_a &= \bar{R}_a + r_a' & \rho &= \bar{\rho} + \rho' \\ k &= \bar{k} + k' & E &= \bar{E} + e' \\ u &= \bar{u} + u' \end{aligned} \quad (26)$$





Substitution of Equations 26 into 25 yields

$$\frac{(\bar{E} + e')^2}{R_w(R_w - \bar{R}_a - r_a')^2} = \left( \frac{\pi \ell}{\alpha R_o} A \right) (\bar{k} + k') + \left( \frac{\pi \ell D}{\alpha R_o} \left[ \frac{C}{Pr} \right]^{1/2} B \right) (\bar{\rho} + \rho')^{1/2} (\bar{u} + u')^{1/2} (\bar{k} + k')^{1/2} \quad (27)$$

According to the Binomial Theorem,

$$\frac{(\bar{E} + e')^2}{R_w(R_w - \bar{R}_a)^2} \cdot \frac{1}{1 - \frac{r_a'}{R_w - \bar{R}_a}} = \frac{(\bar{E} + e')^2}{R_w(R_w - \bar{R}_a)^2} \cdot \left( 1 + \frac{r_a'}{R_w - \bar{R}_a} \right). \quad (28)$$

Note that

$$(\bar{E} + e')^2 \approx \bar{E}^2 + 2\bar{E}e'. \quad (29)$$

Using Equations 28 and 29 for the left side of 27, and expanding the right side of 27, and neglecting small quantities yields:

$$\frac{\bar{E}^2}{R_w(R_w - \bar{R}_a)^2} + \frac{\bar{E}^2 r_a'}{R_w(R_w - \bar{R}_a)^3} + \frac{2\bar{E}e'}{R_w(R_w - \bar{R}_a)^2} = \left( \frac{\pi \ell}{\alpha R_o} A \right) (\bar{k} + k') + \left( \frac{\pi \ell D}{\alpha R_o} \left[ \frac{C}{Pr} \right]^{1/2} B \right) (\bar{\rho} \bar{u} \bar{k} + \bar{\rho} \bar{u} k' + \bar{\rho} u' \bar{k} + \rho' \bar{u} \bar{k})^{1/2}. \quad (30)$$

But

$$(\bar{\rho} \bar{u} \bar{k} + \bar{\rho} \bar{u} k' + \bar{\rho} u' \bar{k} + \rho' \bar{u} \bar{k})^{1/2} \approx (\bar{\rho} \bar{u} \bar{k})^{1/2} \left( 1 + \frac{1}{2} \left[ \frac{k'}{\bar{k}} + \frac{u'}{\bar{u}} + \frac{\rho'}{\bar{\rho}} \right] \right). \quad (31)$$



Thus Equation 30 becomes

$$\begin{aligned} \frac{\bar{E}^2}{R_w(R_w - \bar{R}_a)} + \frac{\bar{E}^2 r_a'}{R_w(R_w - \bar{R}_a)^2} + \frac{2\bar{E}e'}{R_w(R_w - \bar{R}_a)} = & \left( \frac{\pi \ell}{\alpha R_o} A \right) (\bar{k} + k') + \\ & + \left( \frac{\pi \ell D}{\alpha R_o} \left[ \frac{C}{Pr} \right]^{1/2} B \right) (\overline{\rho u k})^{1/2} \left( 1 + \frac{1}{2} \left[ \frac{k'}{k} + \frac{u'}{u} + \frac{\rho'}{\rho} \right] \right). \end{aligned} \quad (32)$$

The time average form of Equation 32 is

$$\frac{\bar{E}^2}{R_w(R_w - \bar{R}_a)} = \left( \frac{\pi \ell}{\alpha R_o} A \right) \bar{k} + \left( \frac{\pi \ell D}{\alpha R_o} \left[ \frac{C}{Pr} \right]^{1/2} B \right) (\overline{\rho u k})^{1/2}. \quad (33)$$

Subtraction of Equation 33 from 32 gives

$$\begin{aligned} \frac{\bar{E}^2 r_a'}{R_w(R_w - \bar{R}_a)^2} + \frac{2\bar{E}e'}{R_w(R_w - \bar{R}_a)} = & \left( \frac{\pi \ell}{\alpha R_o} A \right) k' + \\ & + \left( \frac{\pi \ell D}{\alpha R_o} \left[ \frac{C}{Pr} \right]^{1/2} B \right) \frac{(\overline{\rho u k})^{1/2}}{2} \left( \frac{k'}{k} + \frac{u'}{u} + \frac{\rho'}{\rho} \right). \end{aligned} \quad (34)$$

The following relationships are known:

$$r_a' = R_o \alpha t' \quad k' = n t' \quad \rho' = - \frac{\bar{\rho}}{\rho} \frac{t'}{T_a} \quad (35)$$

Thus Equation 34 becomes

$$\begin{aligned} \frac{\bar{E}^2 R_o \alpha}{R_w(R_w - \bar{R}_a)^2} t' + \frac{2\bar{E}}{R_w(R_w - \bar{R}_a)} e' = & \left( \frac{n \pi \ell}{\alpha R_o} A \right) t' + \\ & + \left( \frac{\pi \ell D}{\alpha R_o} \left[ \frac{C}{Pr} \right]^{1/2} B \right) \frac{(\overline{\rho u k})^{1/2}}{2} \left( n \frac{t'}{k} - \frac{t'}{T_a} + \frac{u'}{u} \right). \end{aligned} \quad (36)$$

Since  $n \frac{t'}{k} - \frac{t'}{T_a} \ll \frac{u'}{u}$ , Equation 36 becomes



$$\begin{aligned}
 \left[ \frac{2\bar{E}}{R_w(R_w - \bar{R}_a)} \right] e' &= \left[ \frac{\pi \ell^{1/2} D^{1/2} C^{1/2} P^{1/2} B^{1/2} \bar{\rho}^{1/2} k^{1/2}}{2 \alpha R_o \text{Pr}^{1/2} \bar{u}^{1/2}} \right] u' + \\
 &+ \left[ \frac{\frac{\pi \ell A}{\alpha R_o} - \frac{\bar{E}^2 R_o \alpha}{R_w(R_w - \bar{R}_a)^2} \right] t'.
 \end{aligned} \tag{37}$$

Equation 37 may be written

$$\begin{aligned}
 e' &= \left[ \frac{R_w(R_w - \bar{R}_a) \pi \ell^{1/2} D^{1/2} C^{1/2} P^{1/2} B^{1/2} \bar{\rho}^{1/2} k^{1/2}}{4 \bar{E} \alpha R_o \text{Pr}^{1/2} \bar{u}^{1/2}} \right] u' + \\
 &+ \left[ \frac{R_w(R_w - \bar{R}_a) \pi \ell A}{2 \bar{E} \alpha R_o} - \frac{\bar{E} R_o \alpha}{2 (R_w - \bar{R}_a)} \right] t'.
 \end{aligned} \tag{38}$$

The coefficient of  $u'$  represents the sensitivity to velocity fluctuations, and the coefficient of  $t'$  represents the sensitivity to temperature fluctuations. These sensitivities could in principle be calculated, since all factors are either measurable quantities, physical properties, or known constants. In practice, however, this calculation yields values of the sensitivities that do not agree with those determined by actual calibration. This discrepancy is due to two of the supposedly known quantities in Equation 38, namely  $\alpha$  and  $B$ . King's value for  $B$ , since it is based on his potential flow assumption, is seriously in error. The value of  $\alpha$  found in tables of physical properties may also be in error because the value of  $\alpha$  applicable to the wire in use depends very strongly on the history of that wire. In addition, contamination of the wire changes the value of  $D$ , the wire diameter, and the wire length  $\ell$  is some



effective length rather than the actual length. Thus it is impossible to accurately determine the sensitivities by direct calculation. Instead the sensitivities are determined by calibration.

Although the expressions for the sensitivities in Equation 38 do not provide quantitative information, they do indicate the direction of variation in the sensitivities as various parameters are changed. Thus, the velocity sensitivity should decrease with increasing velocity, but velocity should not affect the temperature sensitivity to first order. The velocity sensitivity should increase with increasing wire temperature (resistance).

In order to determine the effect of parameter variation on the temperature sensitivity, further consideration of the two terms that comprise it is necessary. Equation 8 shows that, all other parameters remaining constant, an increase in  $T_a$  (i.e. a positive  $t'$ ) requires a decrease in  $E^2$  (i.e. a negative  $e'$ ) in order to maintain the equality. Thus, the overall sign of the temperature sensitivity must be negative. Since all factors are inherently positive, this implies that

$$\frac{\bar{E} R_o \alpha}{2(R_w - \bar{R}_a)} > \frac{R_w (R_w - \bar{R}_a) n \pi \ell A}{2 \bar{E} \alpha R_o} \quad (39)$$

Thus an increase in  $\frac{\bar{E} R_o \alpha}{2(R_w - \bar{R}_a)}$  causes an increase in

the magnitude of the temperature sensitivity, and an increase in

$$\frac{R_w (R_w - \bar{R}_a) n \pi \ell A}{2 \bar{E} \alpha R_o} \quad \text{causes a decrease.}$$

Equation 33 shows that the quantity  $\frac{\bar{E}^2}{R_w (R_w - \bar{R}_a)}$  is independent of  $T_w - \bar{T}_a$ . That is if the parameter  $T_w - \bar{T}_a$  is varied,





$\frac{\bar{E}^2}{R_w(R_w - \bar{R}_a)}$  remains constant. Further if  $\bar{R}_a$  is constant,  $\bar{E}^2$  is proportional to  $R_w^2$ . Now

$$\frac{\bar{E} R_o}{2(R_w - \bar{R}_a)} = \frac{R_w}{\bar{E}} \frac{\bar{E}^2}{R_w(R_w - \bar{R}_a)} \propto R_o, \quad (40)$$

and

$$\frac{R_w(R_w - \bar{R}_a) n \pi \ell A}{2 \bar{E} \propto R_o} = \bar{E} \frac{R_w(R_w - \bar{R}_a)}{\bar{E}^2} \frac{n \pi \ell A}{R_o \propto} \quad (41)$$

Since  $\frac{R_w}{\bar{E}}$  and  $\frac{\bar{E}^2}{R_w(R_w - \bar{R}_a)}$  are independent of  $T_w - \bar{T}_a$ , it

follows from Equation 40 that variation of  $T_w - \bar{T}_a$  has no effect on

$\frac{\bar{E} R_o}{2(R_w - \bar{R}_a)}$  to first order. Similarly it follows from Equation 41 that  $\frac{R_w(R_w - \bar{R}_a) n \pi \ell A}{2 \bar{E} \propto R_o}$  increases linearly with

increasing  $T_w - \bar{T}_a$ . As previously shown, an increase in this term causes a decrease in temperature sensitivity. Thus an increase in  $T_w - \bar{T}_a$  causes a decrease in temperature sensitivity. Thus it appears that velocity fluctuations could be measured directly by operating at very high temperature differences and that temperature fluctuations could be measured directly by operating at very low temperature differences.



If consideration is given to changing the dimensions and material of the wire, further effects on the sensitivities occur. Velocity sensitivity increases with wire length while the temperature sensitivity decreases. An increase in wire diameter causes an increase in velocity sensitivity and no change in temperature sensitivity to first order. An increase in temperature coefficient causes a decrease in velocity sensitivity and an increase in temperature sensitivity.

Once the desired information on trends in sensitivity is recognized, it is convenient to resort to a more compact notation:

$$S_u = \frac{R_w (R_w - R_a) \pi \ell D^{1/2} C^{1/2} B \bar{k}^{1/2} \rho^{1/2}}{4 \bar{E} \alpha R_o P_r^{1/2} \bar{u}^{1/2}} \quad (42)$$

and

$$S_t = \frac{\bar{E} R_o \alpha}{2 (R_w - \bar{R}_a)} - \frac{R_w (R_w - \bar{R}_a) \pi \ell A \pi}{2 \bar{E} \alpha R_o} \quad (43)$$

thus Equation 38 becomes

$$e' = S_u u' - S_T t' \quad (44)$$

Squaring and time averaging yields

$$\overline{e'^2} = \overline{S_u^2} - 2 S_u S_T \overline{u' t'} + S_T^2 \overline{t'^2} \quad (45)$$

The sensitivities  $S_u$  and  $S_T$  must be determined from calibration. This is discussed in the section on procedure. The quantity,  $\overline{e'^2}$ ,



is experimentally measured. From known values of  $\overline{e'^2}$ ,  $S_u$ , and  $S_T$ , a set of simultaneous equations of the form of Equation 39 can be formed. This set can then be solved for  $\overline{u'^2}$ ,  $\overline{u't'}$ , and  $\overline{t'^2}$ . This solution is discussed in the RESULTS section.



## APPARATUS

### Flow System

The flow system is shown schematically in Figure 1. A Craftsman Model 315.16970, 3HP industrial vacuum cleaner was operated as a blower to supply air to the system. A three inch galvanized duct carried the air to the highest point of the flow system where the duct tapered to meet the 1.0625 inch inside diameter Type M copper tubing that comprised the remainder of the loop. The three-inch duct was fitted with a bleed line and damper. The flow rate in the loop could be varied by using the damper to alter the division of air between loop and bleed line. Above the bleed line in the duct was an orifice meter for measuring air flow rate in the loop. (The calibration curve for the orifice meter is given in Appendix B.) In the copper tube, the air passed downward through an 83 inch unheated velocity developing section. This was followed by a 58 inch heating section which was wound with nichrome heating wire and covered with 1.125 inches of pre-formed pipe insulation. Probes were inserted upward into the copper tube as shown. All measurements were made in the end plane of the heating section.

Iron-constantan bulk thermocouples were installed at the beginning of the velocity developing section and at the end of the heating section, and wall thermocouples were installed at the end of the heating section.





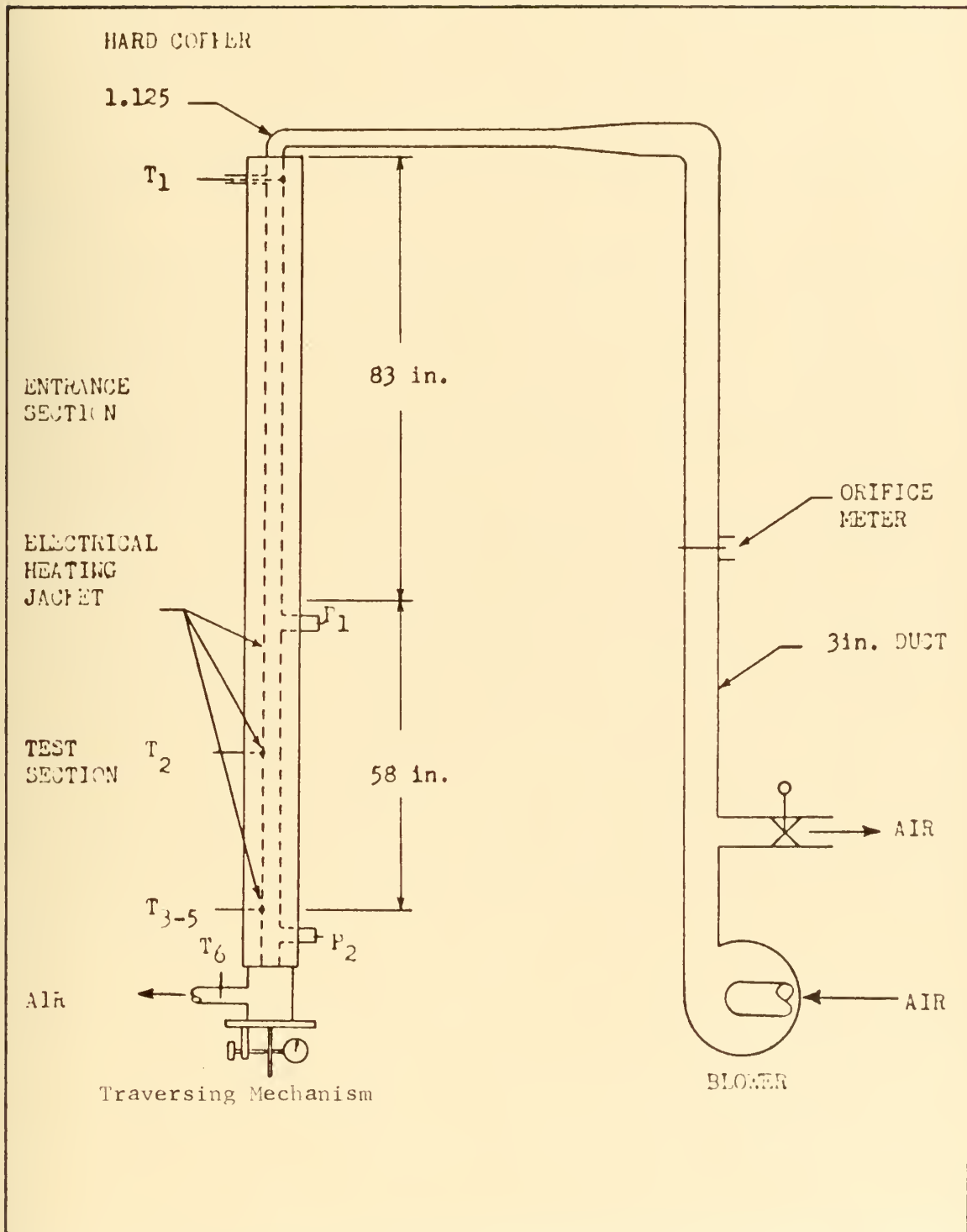


Figure 1. Flow Diagram of Apparatus



### Probes and Traversing Mechanisms

The rapid response thermocouple used (a Heat Technology Laboratory TCFW 202-ChA-5) is shown in Figure 2. The response time of this thermocouple has been estimated by Rodriguez-Ramirez to be 5 milli-seconds.

The hot-wire probe used (a Thermo Systems 1210-T1.5) is shown in Figure 3.

Positioning of the rapid response thermocouple was by means of the traversing mechanism shown in Figure 4. When in place as shown in Figure 1 the mechanism was, of course, inverted. The ball joint permitted radial movement of the probe across the tube. Radial position was measured with the dial guage shown.

Figure 5 shows the traversing mechanism used to position the hot-wire in the loop. This traversing mechanism replaced the thermocouple traversing mechanism at the bottom of the loop when hot-wire measurements were being made. The upper block in Figure 5 could be moved laterally so as to place the hot-wire probe at the desired radial position, while the lower plate shown in Figure 5 was bolted to the loop. A pitot tube and a local mean thermocouple were inserted through the auxiliary probe entrances.



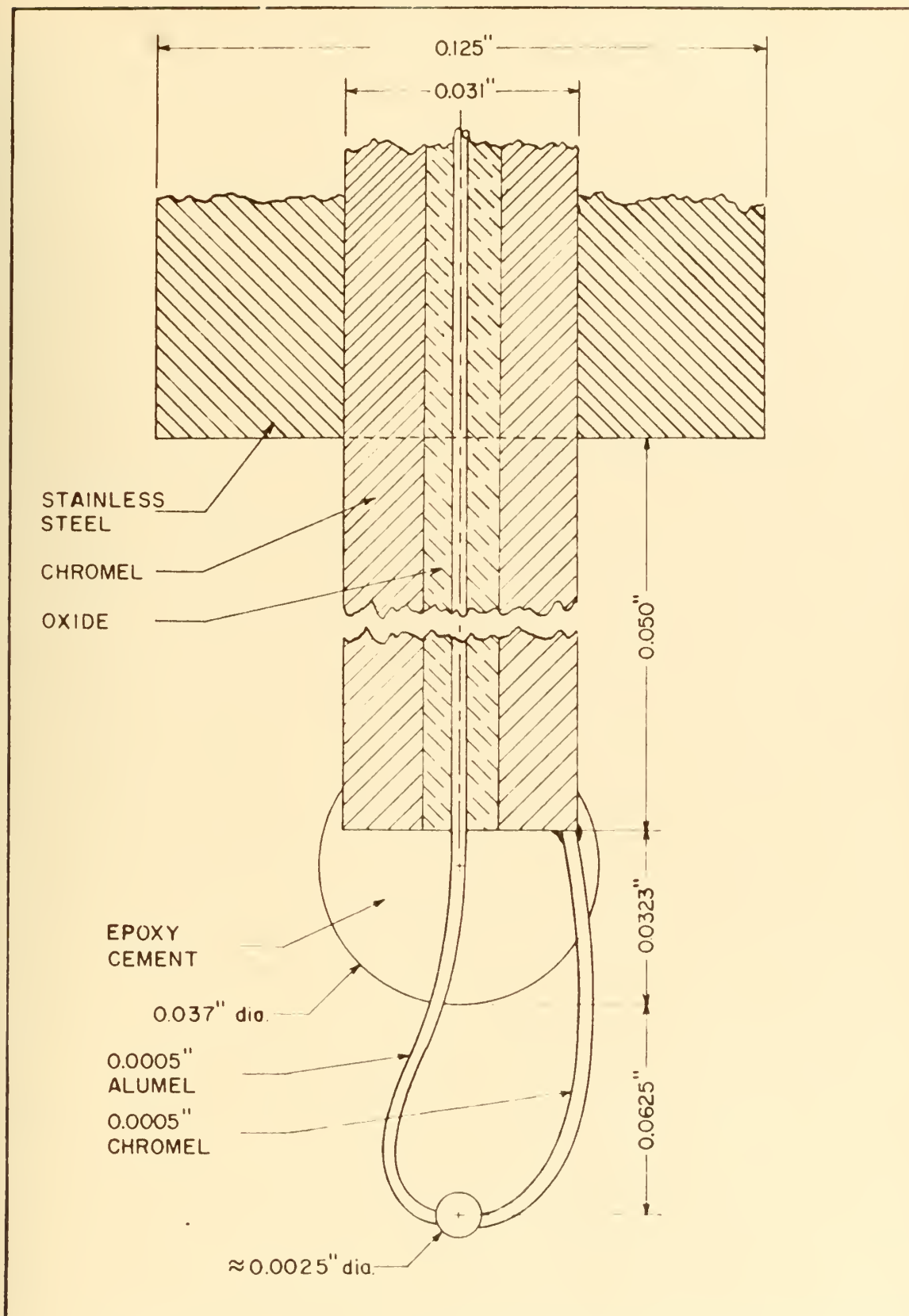


Figure 2. Fast Response Thermocouple



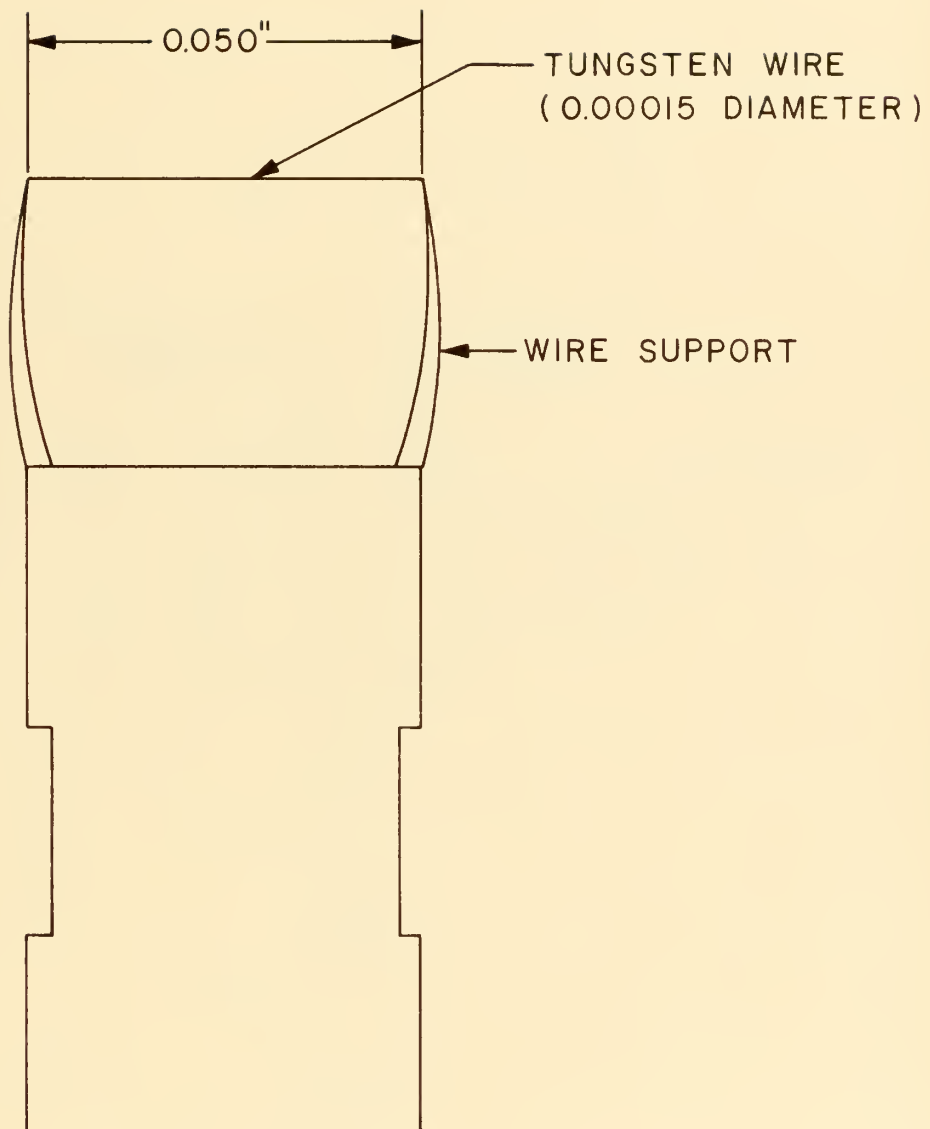


Figure 3. The Hot-Wire Probe





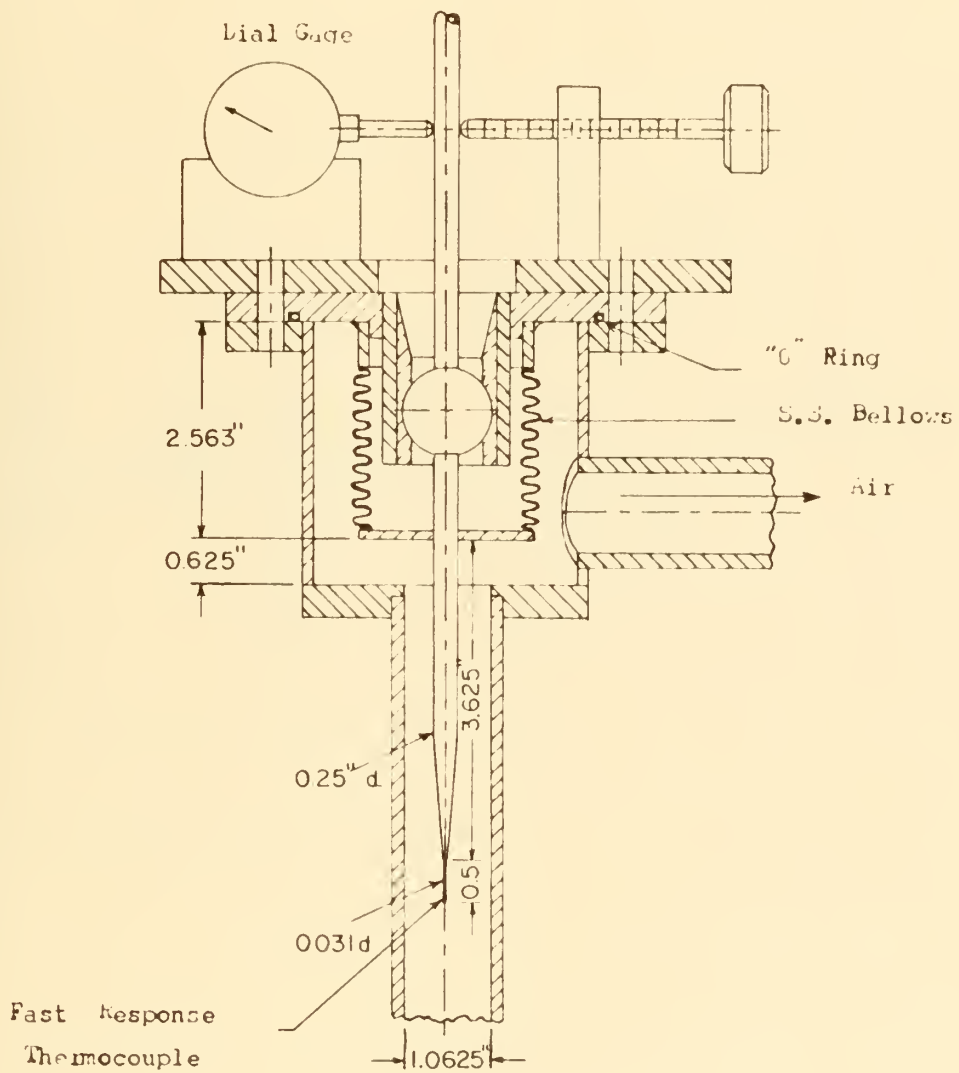


Figure 4. Thermocouple Traversing Mechanism



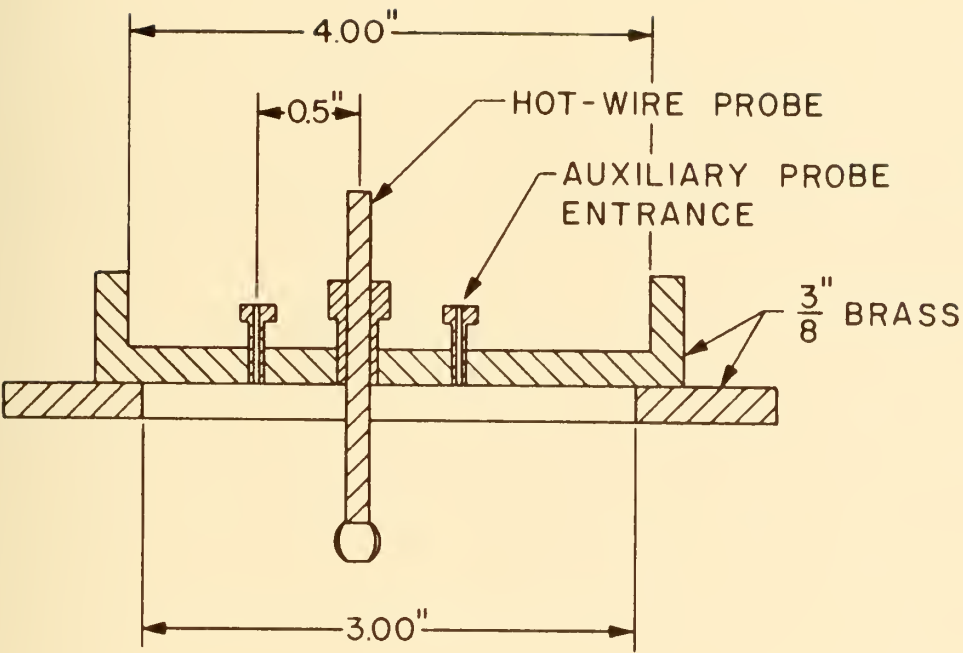


Figure 5. Hot-Wire Traversing Mechanism



### Instrumentation

Instrumentation for hot-wire measurements consisted of a Thermo Systems Type 1010 anemometer, and a Ballantine Model 320A True Root-Mean-Square Electronic Voltmeter.

For rapid-response thermocouple measurements, instrumentation consisted of a Tektronix 122 Amplifier (See Appendix C for frequency response.) and the Ballantine Voltmeter.

Bulk and wall thermocouple measurements were made with a Dana Model 2850 D.C. amplifier and a Beckman Model 4011R digital voltmeter.



## PROCEDURE

Hot-wire in Isothermal Flow

The first step was calibration. The constant  $C$  defined by Equation 17 and appearing in Equation 18 can be determined from mean voltage and velocity measurements. It is seen from Equation 14 that if  $\frac{\bar{E}^2}{R_w(R_w - R_a)}$

were plotted as a function of  $\bar{u}^{\frac{1}{2}}$ , the result should be a straight line with slope  $C$ .

The Calibration of the hot-wire probe was carried out with the probe in place in the loop and located at the tube centerline. Variation of  $\bar{u}$  was achieved by varying the flow rate in the loop using the bleed line damper. The quantity  $\bar{E}$  was measured at seven or eight different flow rates. The value of  $\bar{u}$  at the centerline corresponding to each flow rate was measured with a pitot tube. The data were plotted as indicated above, a straight line was fitted to the points, and the slope was measured. Calibration curves are shown in Appendix E.

The second step was the making of fluctuation measurements. Equation 18 gives the relationship between the rms velocity fluctuation and the rms voltage fluctuation.

The flow system was operated at Reynolds Numbers of 30,700, 41,500, and 49,800. For each Reynolds Number, measurements were made of  $\sqrt{e'^2}$  at eight points between the center and the wall of the tube corresponding to  $r/R$  of 0, 0.125, 0.250, 0.375, 0.500, 0.625, 0.750 and 0.875. A





pitot tube was used to measure  $\bar{u}$  at the same points.

After all fluctuation measurements had been made, the calibration procedure was repeated to make certain that the constant C had not changed during the run.

#### Rapid Response Thermocouple in Non-Isothermal Flow

The flow was adjusted so that the Reynolds Numbers in this part were the same as those in the previous section. The applied heating was 430 watts in all cases.

Measurement was made of  $\sqrt{e'^2}$  from the rapid response thermocouple as a function of radial position for each Reynolds Number. No calibration was done, since the constant, a, in Equation 24 was assumed to be that found in standard thermocouple tables<sup>13</sup>. This assumption is of questionable validity.

A conventional thermocouple was used to measure the centerline temperature, and the wall thermocouples were used to measure the wall temperature for each Reynolds Number.

#### Hot-Wire in Non-Isothermal Flow

The procedure of calibration and measurement outlined below represents one of the contributions of this work. It is anticipated that this procedure will be used for the glycol and mercury measurements previously mentioned.

As shown in the THEORETICAL BACKGROUND section, the sensitivities  $S_u$  and  $S_T$  depend on two parameters:  $\bar{u}$  and  $T_w - \bar{T}_a$ . Thus, in calibration it is necessary to determine the functional dependence on each parameter.

Calibration for temperature sensitivity was also carried out with



the probe in place and at the tube centerline. Velocity variation was again achieved by use of the bleeder line damper, and  $\bar{u}$  was measured with a pitot tube. In this way five different values of  $\bar{u}$  were used, and for each value of  $\bar{u}$  thirteen values of  $T_w - \bar{T}_a$  were used.

These data were plotted as  $\bar{E}$  versus  $\bar{u}$  for constant values of  $T_w - \bar{T}_a$  and as  $\bar{E}$  versus  $T_w - \bar{T}_a$  for constant values of  $\bar{u}$ . These curves are shown in Appendix G. The sensitivities  $S_u$  and  $S_T$  are the derivatives of these curves. These derivatives were obtained from analytical differentiation of parabolas fitted to the data by the method of least squares. The selection of parabolas is arbitrary, but the relatively slow and smooth variation of the data makes a parabola a satisfactory approximation.

Note that  $T_w - \bar{T}_a$  must be computed from measurements made of  $R_w - \bar{R}_a$ . The resistance-temperature characteristic of the hot-wire probe was experimentally determined to be as shown in Appendix D.

Once  $S_u$  and  $S_T$  were known as functions of  $\bar{u}$  and  $T_w - \bar{T}_a$ , fluctuation measurements were made. The rms voltage fluctuation was measured at  $r/R = 0$  and  $r/R = .5$  for each flow rate and temperature difference considered in calibration.

When all fluctuation measurements had been completed, the calibration was repeated to determine the drift in  $S_u$  and  $S_T$ .



## RESULTS

### Hot-Wire in Isothermal Flow

Figure 6 shows the axial turbulent intensity at the centerline of the pipe compared with the work of Sandborn.<sup>11</sup>

Figure 7 shows axial turbulent intensity as a function of radial position for three different Reynolds Numbers compared with the work of Laufer.<sup>10</sup>

The agreement of present results with those of Sandborn<sup>11</sup> and Laufer<sup>10</sup> is rather good. The data used by Sandborn to obtain his correlation show a scatter of  $\pm 10$  percent. The results of the present work are well within this range.

### Rapid Response Thermocouple in Non-Isothermal Flow

Figure 8 shows the temperature fluctuation intensity as a function of radial position. Rodriguez-Ramirez<sup>14</sup>, and also Tanimoto and Hanratty<sup>15</sup> have published results of this nature. The present results are for a range of Reynolds Numbers higher than the range considered by Rodriguez-Ramirez; however, a preliminary run was made in which the flow rate and heat input were the same as those in one of Rodriguez-Ramirez' runs. The results of this run deviated from those of Rodriguez-Ramirez by less than 5 percent. The temperature gradients used by Tanimoto and Hanratty were so much larger than those used in the present work that comparison is not possible.



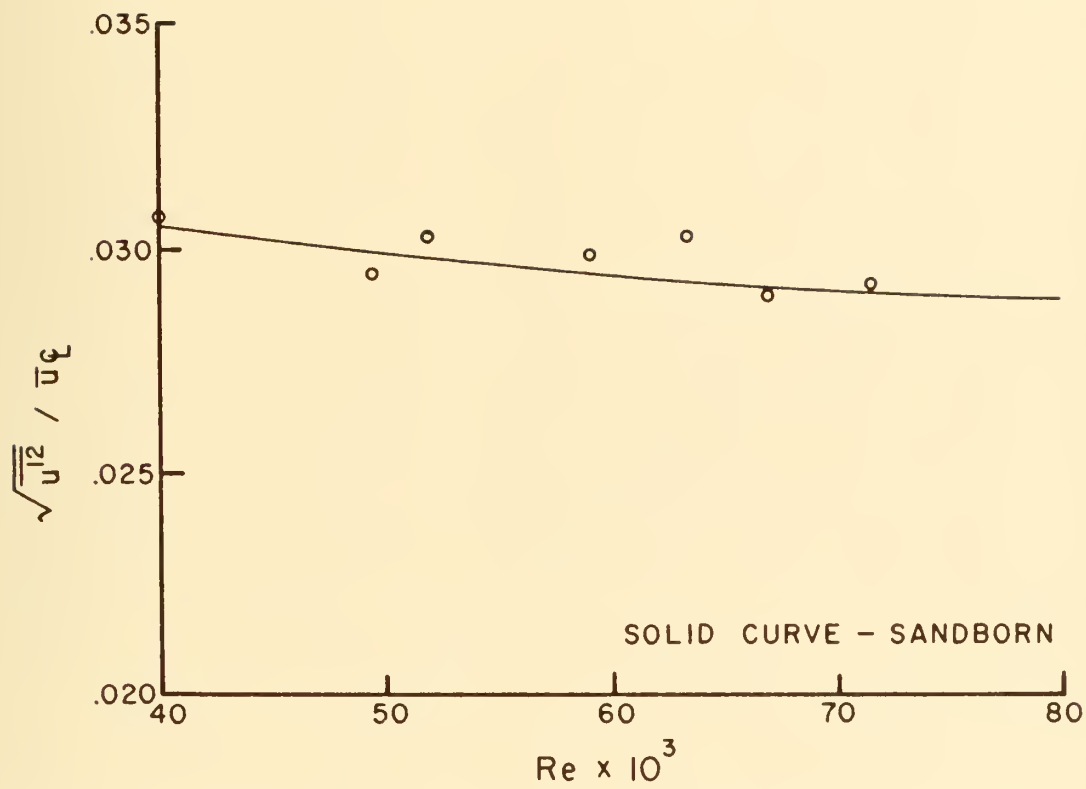


Figure 6. Centerline Velocity Turbulence Intensity in Air





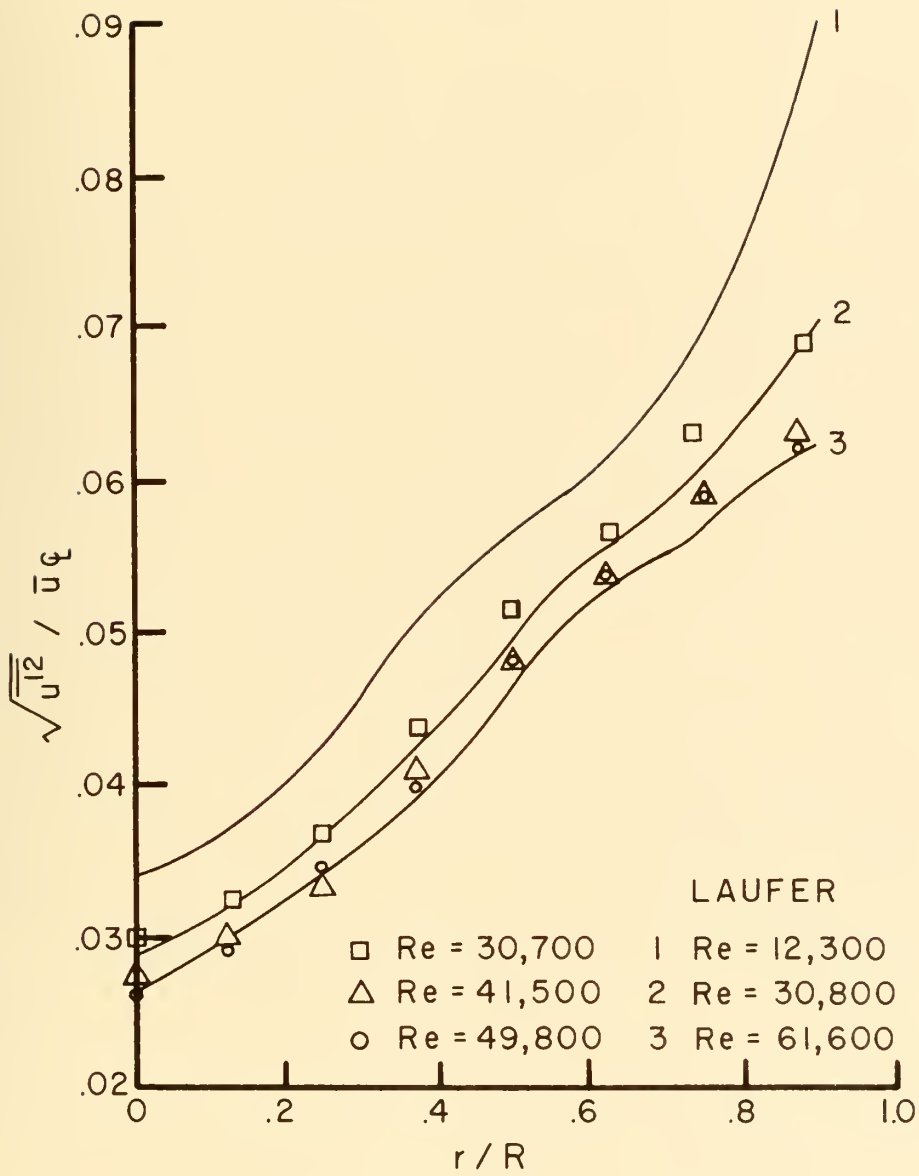


Figure 7. Velocity Turbulence Intensity in Air I



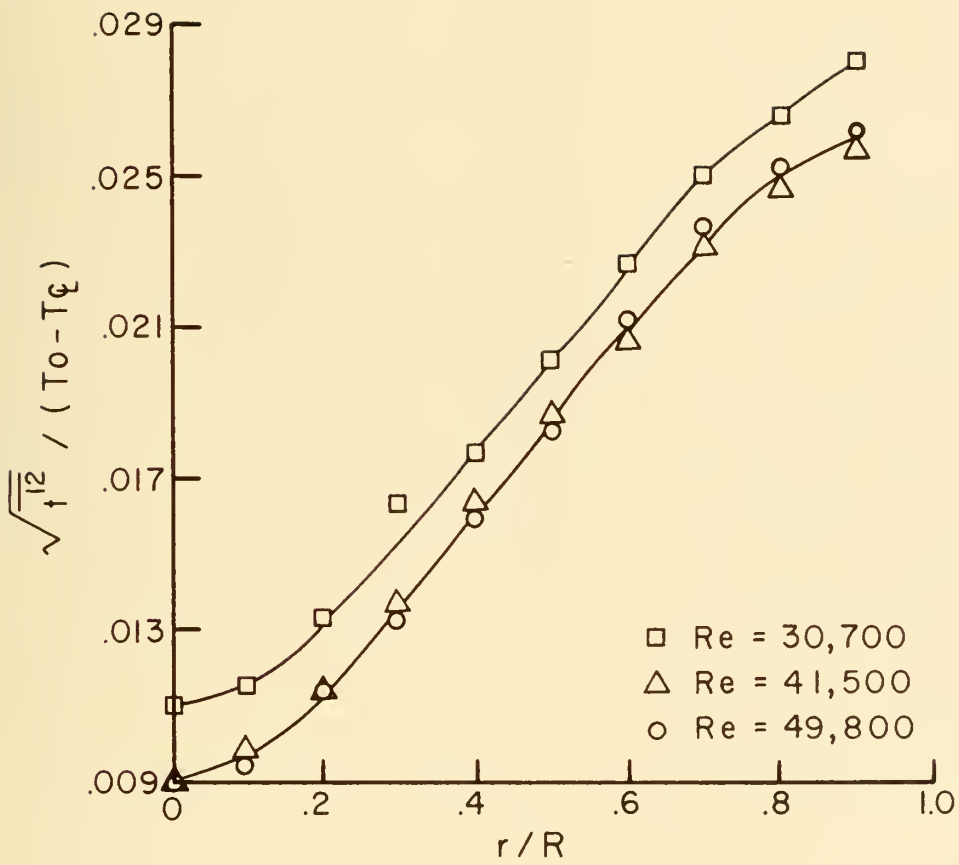


Figure 8. Temperature Turbulence Intensity in Air



### Hot-Wire in Non-Isothermal Flow

Figures 9 and 10 show the dependence of the sensitivities  $S_u$  and  $S_T$  on the parameters  $\bar{u}$  and  $T_w - \bar{T}_a$ . The velocity sensitivity,  $S_u$ , increases with increasing temperature difference and decreases with increasing velocity as predicted from Equation 38. The temperature sensitivity decreases with increasing temperature difference as predicted from Equation 38. Note that there is a secondary dependence on velocity not predicted by Equation 38. This dependence is due to the velocity dependence of the effective wire length.

The investigation of various calculating schemes including the selection of the best one for analyzing the non-isothermal data was an important part of the present work. As pointed out in the section on theoretical development, Equation 45 gives the relationship between the unknown quantities  $\overline{u'^2}$ ,  $\overline{u't'}$  and  $\overline{t'^2}$  and the known quantities  $S_u$ ,  $S_T$ , and  $\overline{e'^2}$ . Since there are three unknowns, at least three equations of the form of Equation 39 are needed. These can be obtained by operating the hot-wire at least three values of  $T_w$  (and hence of  $T_w - \bar{T}_a$ ). For each value of  $T_w - \bar{T}_a$ , the values of  $S_u$  and  $S_T$  appropriate to the mean velocity,  $\bar{u}$ , of the flow are read from Figures 9 and 10, and  $\overline{e'^2}$  is measured. Thus, for each value of  $T_w - \bar{T}_a$  an equation is formed.

Once the set of equations is obtained, a number of methods of solution are available. The most obvious one is the simultaneous solution of three such equations by a method such as Gaussian reduction.<sup>16</sup> However, the numerical calculations involve the subtraction of large numbers whose difference is small, which has the effect of greatly magnifying the errors in the data. Since the errors in  $S_u$  and  $S_T$  were already large, the result was errors in the calculated values of  $\overline{u'^2}$ ,  $\overline{u't'}$ , and  $\overline{t'^2}$  of the



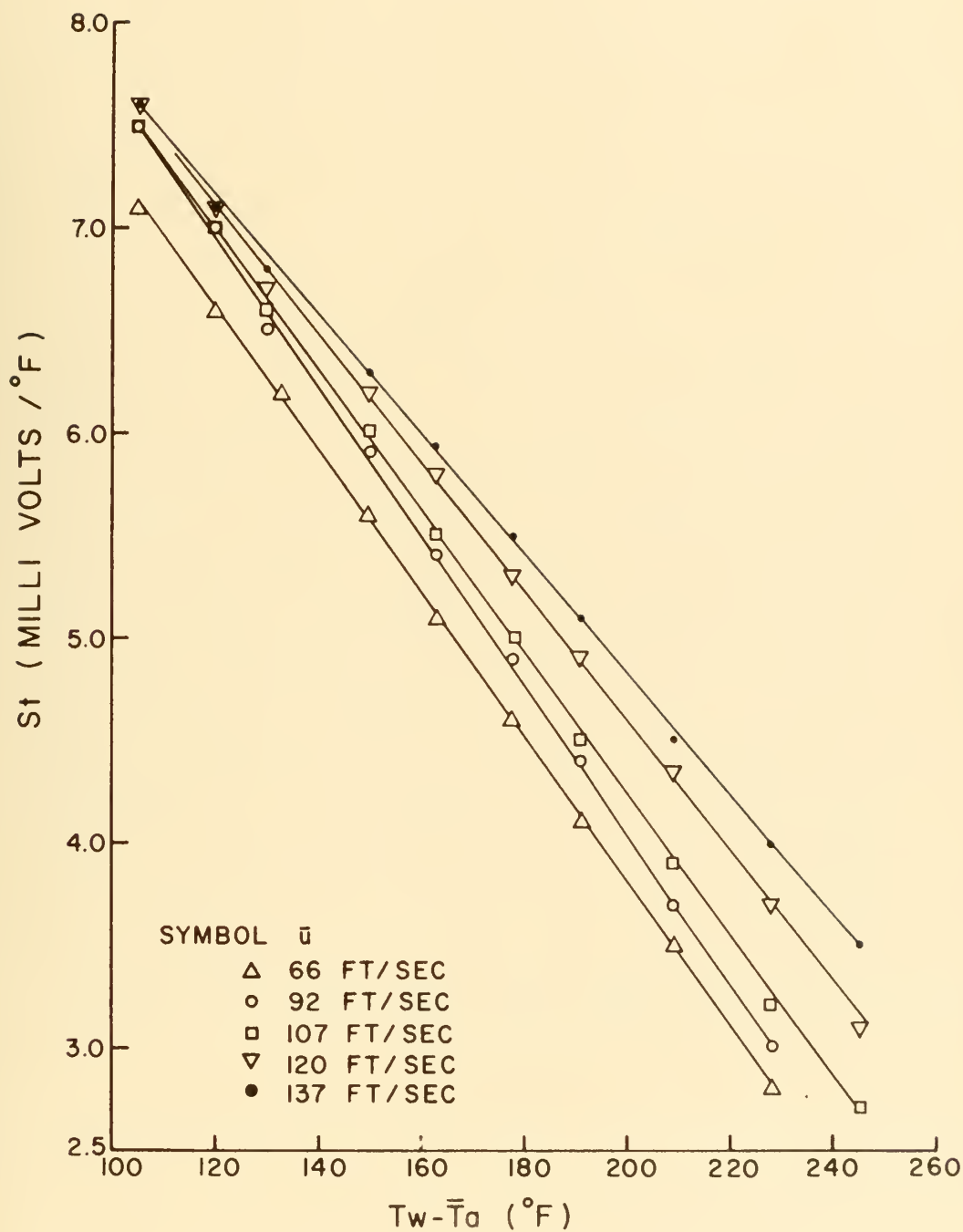


Figure 9. Hot-Wire Temperature Sensitivity





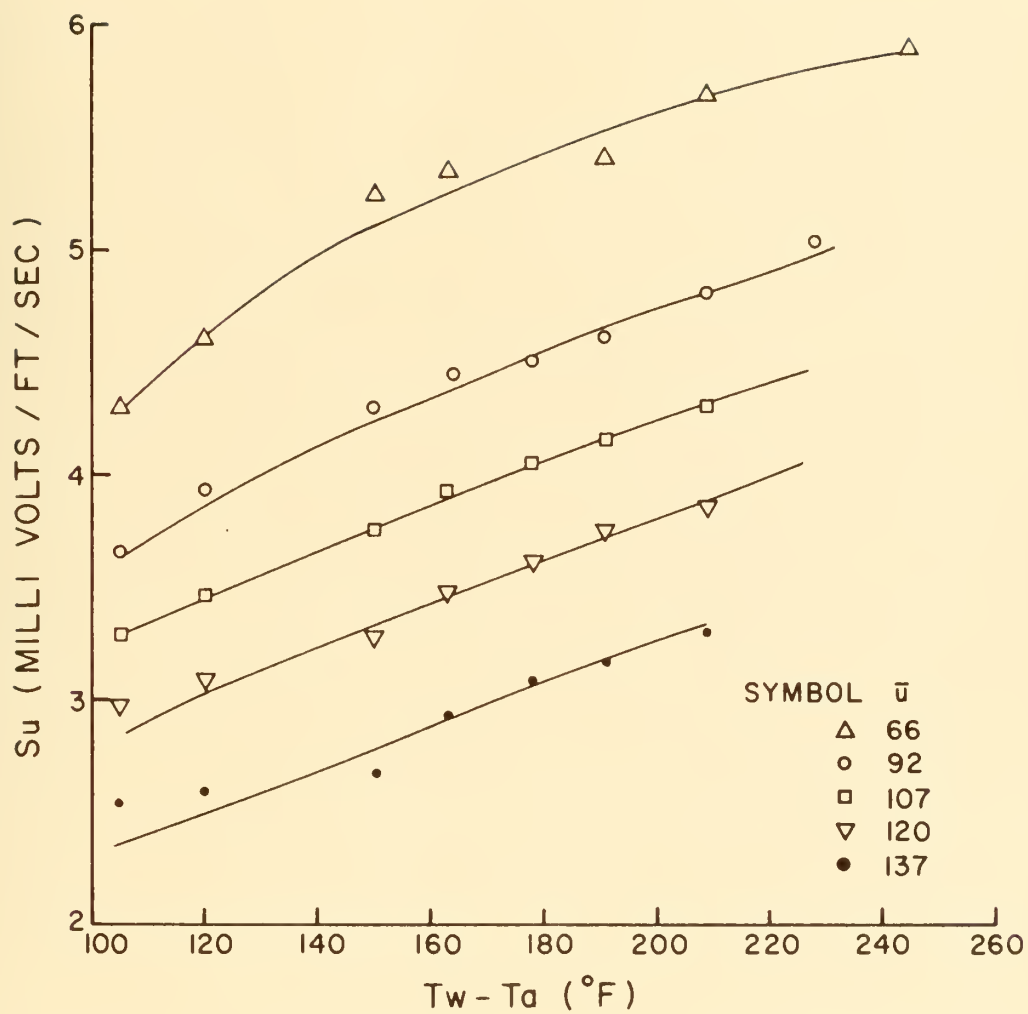


Figure 10. Hot-Wire Velocity Sensitivity



order of 500 percent.

The Kovaszny Fluctuation Diagram<sup>17</sup> is a graphical method of solving the set of equations in which equation 39 is divided by  $S_T^2$  to give:

$$\frac{\overline{e'^2}}{S_T^2} = \left( \frac{S_u}{S_T} \right)^2 \overline{u'^2} - 2 \left( \frac{S_u}{S_T} \right) \overline{u't'} + \overline{t'^2}. \quad (46)$$

Then the quantity  $\frac{\overline{e'^2}}{S_T^2}$  is plotted versus  $\frac{S_u}{S_T}$ . Note that analytically the relationship between the two is described by a parabola. By the method of least squares a parabola is fitted to the data. The computer program used to do this fitting is listed in Appendix F. The intercept of this parabola with the  $\frac{\overline{e'^2}}{S_T^2}$  axis is  $\overline{t'^2}$ , the slope at  $\frac{S_u}{S_T} = 0$  is  $-2\overline{u't'}$ , and the curvature of the parabola is  $\overline{u'^2}$ . This method was used on the present data, but the need to extrapolate the data from  $\frac{S_u}{S_T}$  of some non-zero value to  $\frac{S_u}{S_T} = 0$  and then determine the slope at  $\frac{S_u}{S_T} = 0$  resulted in a large uncertainty in  $\overline{u't'}$ . This same problem was encountered by Arya and Plate<sup>9</sup>, who suggested that if an independent measurement of  $\overline{t'^2}$  could be obtained to locate the intercept of the curve accurately, then reliable values of the remaining two unknowns  $\overline{u't'}$  and  $\overline{u'^2}$  could be determined by the Kovaszny method. This procedure was followed with the present data. The value of  $\overline{t'^2}$  used was the value found using the rapid response thermocouple. The results were still rather uncertain, but the uncertainty was less than for any of the other methods. (The Kovaszny Fluctuation Diagrams for representative cases are shown in Appendix H.)

The numerical values of  $\sqrt{\overline{u'^2}/\overline{u}}$  presented in Figures 11 and 12 deviate seriously from the isothermal results with which it is thought they should agree. (See, for instance Corrsin and Uberoi<sup>5</sup>) The trends



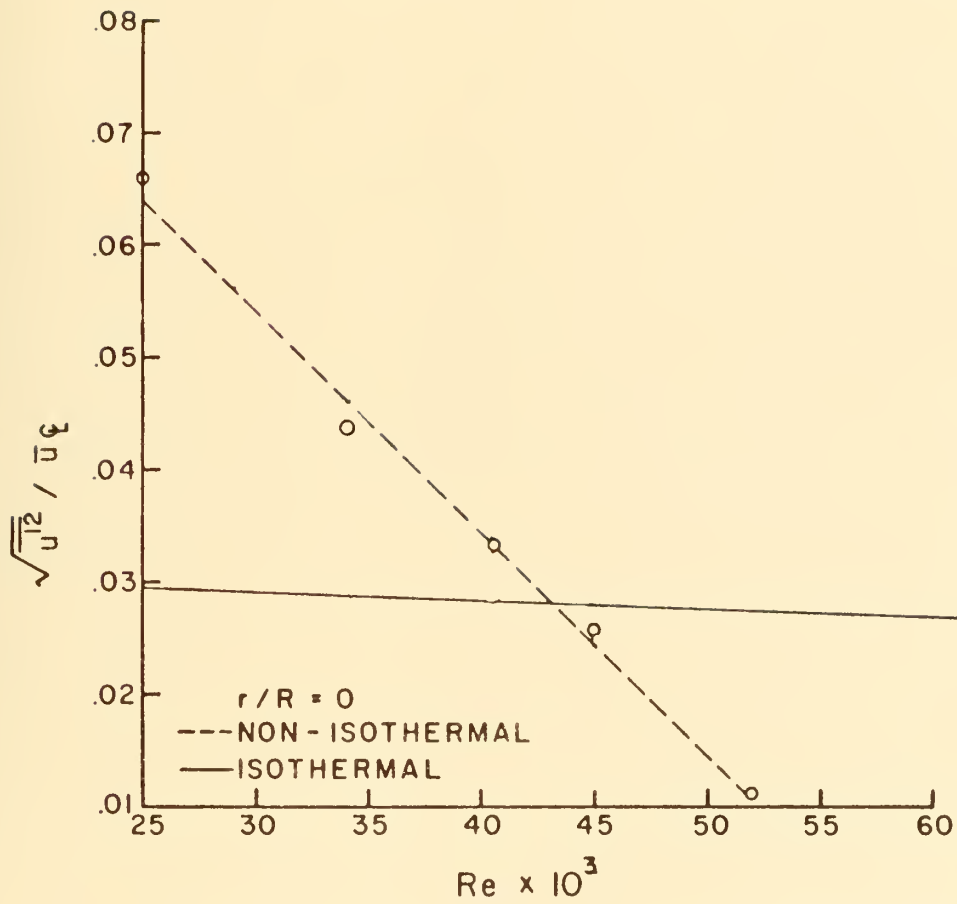


Figure 11. Velocity Turbulence Intensity in Air II



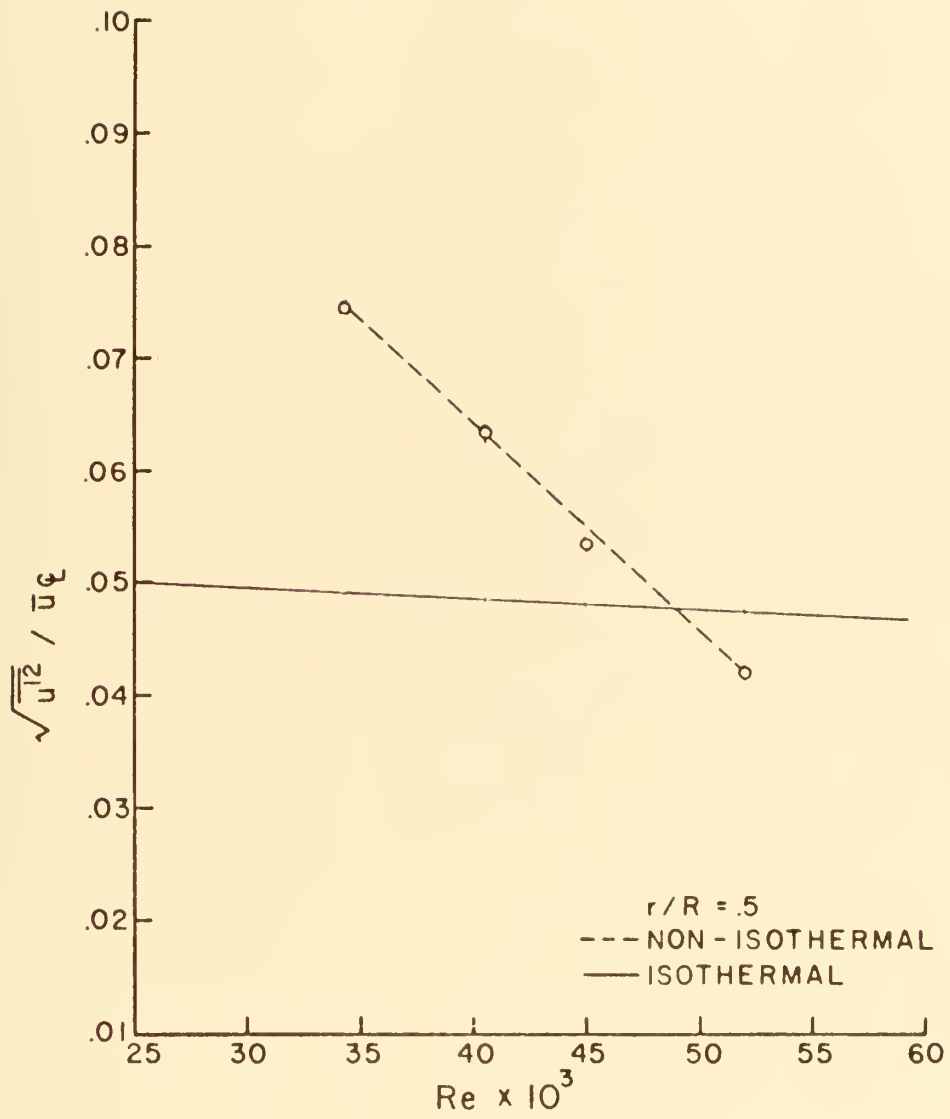


Figure 12. Velocity Turbulence Intensity in Air III





of the results with Reynolds Number and radial position are in accordance with expectations.

The calculated values of  $\overline{u't'}/\bar{u}_L (T_o - T_L)$  are presented in Figure 13. Turbulence at the centerline in pipe flow for the Reynolds numbers used in the present work should be isotropic. Thus  $\overline{u't'}$  and  $\overline{u't'}/\bar{u}_L (T_o - T_L)$  should both be zero at the centerline. The centerline results in Figure 13 do not exhibit this behavior. However the error in these results is roughly estimated in Appendix I as 100%.

Away from the centerline the turbulence should no longer be isotropic, and  $\overline{u't'}$  should no longer be zero. With heating from the wall as in the present case,  $\overline{u't'}$ , and hence  $\overline{u't'}/\bar{u}_L (T_o - T_L)$  should be negative. This trend is followed by the present results in that  $\overline{u't'}/\bar{u}_L (T_o - T_L)$  at  $r/R = .5$  has a larger magnitude than at  $r/R = 0$  and in that it has a negative sign. The quantity  $\overline{u't'}/\bar{u}_L (T_o - T_L)$  cannot continue to increase indefinitely as Reynolds Number increases, for this would mean no dissipation was taking place. The increasing trend in the results shown in Figure 13 for  $r/R = .5$  is therefore not anticipated, but it is possible so long as the trend reverses itself at higher Reynolds Numbers. Arya and Plate<sup>9</sup> found that in the boundary layer growing on the wall of a wind tunnel  $\overline{u't'}/\bar{u}_L (T_o - T_L)$  remained nearly constant with increasing Reynolds Number. Again with an estimated error of 100 percent little significance can be attached to present results.



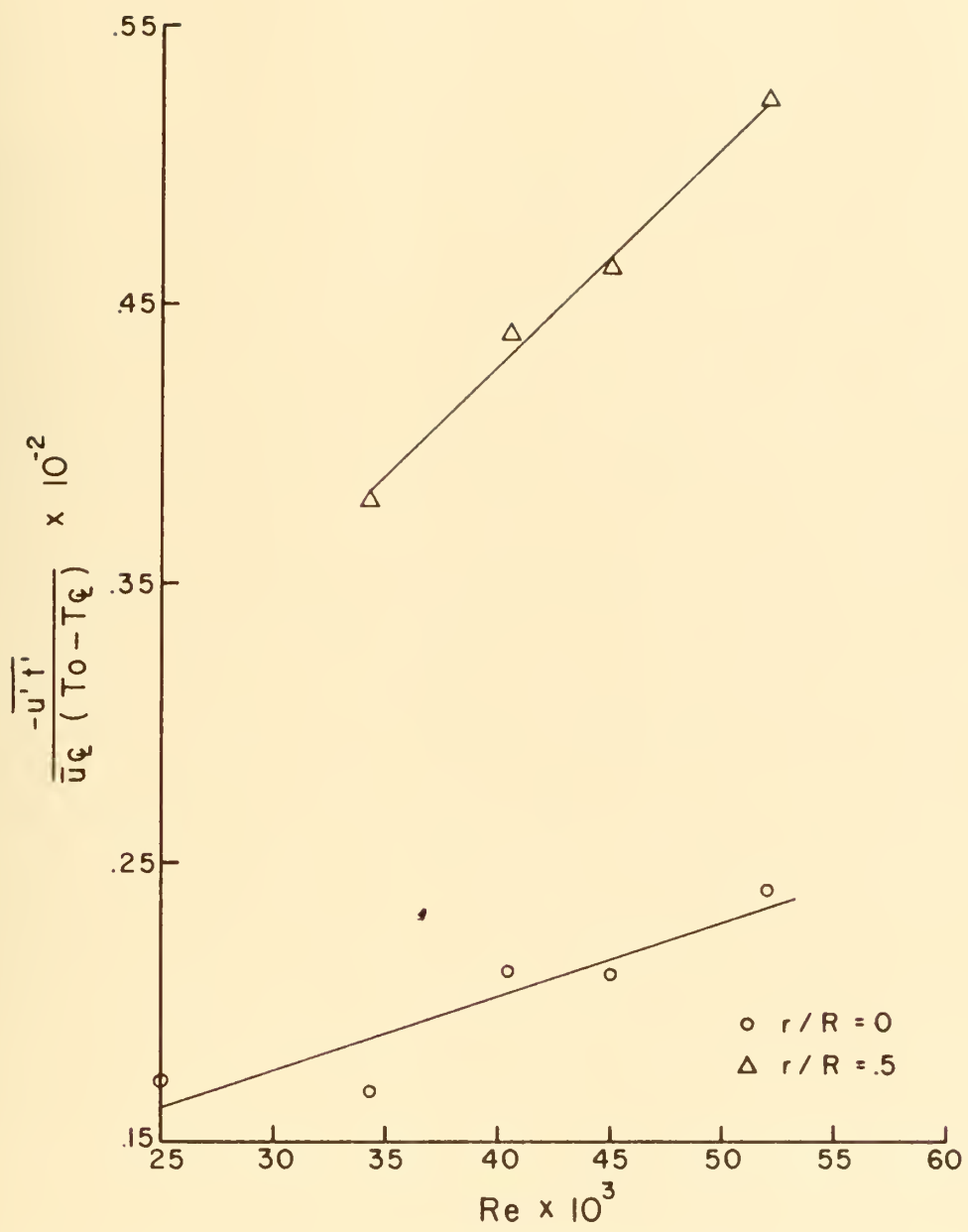


Figure 13. Temperature-Velocity Turbulence Intensity in Air



## DISCUSSION

The numerical results for  $\sqrt{\overline{u'^2}}/\bar{u}_L$  and  $\overline{u't'}/\bar{u}_L$  are in general, too large. In view of the way in which these intensities are obtained from the Kovasznay Fluctuation Diagram, this suggests that  $S_u$  is too small. The temperature sensitivity  $S_T$  affects both coordinates in the same way, and therefore, errors in  $S_T$  would be self-compensating. However, errors in  $S_u$  affect only the  $\frac{S_u}{S_T}$  coordinate. Too small a value of  $S_u$  would cause too large a slope and curvature in the fitted parabola and too large a value of  $\overline{u'^2}$  and  $\overline{u't'}$ .

Because of the long time required for the system to come to thermal equilibrium after each change in flow rate, the data used to compute  $S_u$  for a given value of  $T_w - \bar{T}_a$  were taken over a period of approximately eight hours. It is reasonable to expect an increase in the thickness of the layer of contamination on the wire during this period since the wire was continuously exposed to an inadequately filtered flow.

Kronauer<sup>3</sup> has shown that dirt accumulations on fine wires at low flow rates increase the heat transfer rate because the heat transfer area increases more rapidly than the heat transfer resistance as dirt accumulates. Thus, a dirty wire would require a higher value of  $\bar{E}$  than a clean one to maintain it at a given temperature.



The wire used for the present measurements was examined under a microscope, and a significant amount of dirt was observed on it.

In the present calibration,  $\bar{E}$  was measured at the highest calibration velocity first, and the velocity was decreased step by step until the lowest value was reached. As anticipated,  $\bar{E}$  decreased with decreasing velocity, but the increasing layer of contamination apparently worked counter to this trend. Thus, in the calibration procedure used the rate of decrease of  $\bar{E}$  was slower than if contamination had not been a problem. The result was a value of  $S_u$  that was too small.

Larger values of  $S_u$  would result in larger values of  $\frac{S_u}{S_T}$  at the same value of  $\frac{\overline{e'^2}}{S_T^2} - \overline{t'^2}$  on the Kovasznay Fluctuation Diagram and thus, a

smaller slope and curvature of the fitted parabola. The calculated values of  $\sqrt{\overline{u'^2}}$  and  $\overline{u't'}$  would then be smaller and in better agreement with the isothermal results.

It was not possible to determine the errors in  $\sqrt{\overline{u'^2}}$  and  $\overline{u't'}$  caused by the drift in  $\bar{E}$  noted above because it was not possible to measure what  $\bar{E}$  would have been without contamination. Thus it was necessary to use a different method to estimate these errors. The method used is outlined in Appendix I, and the error estimates are 36 percent in  $\sqrt{\overline{u'^2}}$  and 100 percent in  $\overline{u't'}$ . As noted in Appendix I, these figures do not represent true confidence limits on the results. They are only rough estimates of the errors present.

The calibration curves for before and after as shown in Figures 24 through 26 show such a large drift that all data taken in between should be discarded. This was not done, since a number of attempts to obtain





better results failed. Note then, that all fluctuation intensities obtained from the present non-isothermal hot-wire measurements are of very doubtful reliability.

Due to inexperience in this area, a number of deviations from good experimental practice were present. First, although the wire was examined under a microscope after all measurements had been made, no examination was made before or during experimental runs. Thus the hypothesis of an increasing dirt layer cannot be verified. Second, no attempt was made to clean the wire during the course of experimental runs. Because of these errors it is not possible to analyze in detail or to correct for the drift that occurred.

In future work, provision should be made for careful filtration of the fluid and a means of rapid calibration to minimize drift. Two calibrations, one with increasing velocity and one with decreasing velocity, should be made to check for contamination. If it is still not possible to reduce drift to an acceptable level, provision should be made for the complete withdrawal of the probe from the flow.

A problem encountered with the present apparatus was difficulty in maintaining flow rate and heat input at desired levels. Long term temperature variations of two or three degrees persisted even after the system had come to "equilibrium". This was apparently caused by cycling of the room temperature.

The nature of the problems encountered in the present work serve as a guide in planning additional steps in the overall research program.



## SUMMARY AND CONCLUSIONS

This work has developed procedures for the calibration of a hot-wire in non-isothermal flow. Further, the various calculation schemes available for analyzing non-isothermal flow fluctuation data have been evaluated and the Arya and Plate<sup>9</sup> modification of the Kovasznay Fluctuation Diagram<sup>17</sup> method has been found to be the most satisfactory.

Apparatus limitations and deviations from good experimental practice precluded the production of reliable numerical results.

The findings of this investigation are an important preliminary step in a comprehensive research program of non-isothermal flow measurements with hot-wire and hot-film anemometers.



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## APPENDICES



## APPENDIX A



## APPENDIX A

## TABLES OF EXPERIMENTAL DATA

Table 1

## Orifice Meter Calibration

$\Delta P$ Orifice Meter (in)*	$\Delta P$ Pitot Tube At (in)*
4.553	2.173
3.151	1.595
2.172	1.123
1.114	0.571

\* Manometer Fluid SPG. 0.797





Table 2

## Tektronix Amplifier Frequency Response

Frequency (CPS)	Voltage in (Millivolts)	Voltage Out (Volts)
5	.200	.200
7	.200	.214
9	.200	.222
20	.200	.238
40	.200	.244
60	.200	.245
80	.200	.245
100	.200	.244
200	.200	.239
300	.200	2.31
400	.200	.226
500	.200	.217
600	.200	.210
700	.200	.200
800	.200	.193
900	.200	.185
1000	.200	.177
1100	.200	.170



Table 3

Calibration for Isothermal Re=49,800 Run

$\Delta P$ Pitot Tube	(in of SPG.797 Fluid)	$R_a$ (OHM)	$R_w$ (OHM)	$\bar{E}$ (VOLTS)	$\sqrt{e'^2}$ (MILLIVOLTS)
3.890		7.57	10.60	3.07	13.0
3.394		7.54	10.56	3.04	13.0
2.948		7.52	10.53	2.98	12.9
2.407		7.50	10.50	2.93	12.8
1.935		7.48	10.47	2.88	12.7
1.369		7.46	10.44	2.81	12.5
0.844		7.43	10.40	2.71	12.5
0.330		7.38	10.33	2.54	12.6
Before †					
4.004		7.57	10.60	3.08	-----
0.737		7.42	10.39	2.70	-----
After †					



Table 4

Data for Isothermal Re=49,800 Run

Radial Position (in)	$\Delta P$ Pitot Tube	(in of SPG.797 Fluid)	$\bar{E}$ (Volts)	$\sqrt{e'^2}$ (Millivolts)
0.0000		3.984	3.07	12.9
0.0625		3.964	3.07	12.9
0.1250		3.841	3.07	16.5
0.1875		3.691	3.06	19.5
0.2500		3.433	3.04	23.6
0.3125		3.184	3.02	27.5
0.3750		2.870	2.97	31.7
0.4375		2.411	2.94	36.4

Table 5

Calibration for Isothermal Re=30,700 and 41,500 Runs

$\Delta P$ Pitot Tube (in. of SPG.797 Fluid)	$R_a$ (Ohms)	$R_w$ (Ohms)	$\bar{E}$ (Volts)	$\sqrt{e'^2}$ (Millivolts)
3.533	7.55	10.57	3.05	12.8
2.999	7.53	10.54	2.98	12.6
2.500	7.51	10.51	2.94	12.5
2.000	7.48	10.47	2.88	12.4
1.496	7.46	10.44	2.82	12.4
1.020	7.44	10.42	2.75	12.3
0.500	7.40	10.36	2.61	12.4
Before $\uparrow$				
2.780	7.52	10.53	2.96	----
1.020	7.44	10.42	2.75	
After $\uparrow$				



Table 6

Data for Isothermal Re=30,700 Runs

Radial Position (in.)	$\Delta P$ Pitot Tube (in.SPG.797 Fluid)	$\bar{E}$ (Volts)	$\sqrt{e'^2}$ (Millivolts)
0.0000	1.480	2.81	12.2
0.0625	1.460	2.81	12.9
0.1250	1.400	2.80	15.1
0.1875	1.330	2.79	18.2
0.2500	1.240	2.78	21.9
0.3125	1.130	2.76	24.8
0.3750	1.020	2.74	28.6
0.4375	0.850	2.71	32.5

Table 7

Data for Isothermal Re=41,500 Run

Radial Position (in.)	$\Delta P$ Pitot Tube (in.SPG797 Fluid)	$\bar{E}$ (Volts)	$\sqrt{e'^2}$ (Millivolts)
0.0000	2.780	2.95	12.4
0.0625	2.730	2.95	13.4
0.1250	2.630	2.95	15.6
0.1875	2.500	2.94	19.0
0.2500	2.330	2.92	22.6
0.3125	2.150	2.90	26.2
0.3750	1.960	2.89	29.4
0.4375	1.650	2.85	34.2





Table 8

Thermocouple Data for Re=30,700 Run

Radial Position (in)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	NOISE
$\sqrt{e'^2}$ (Milli- volts)	20.0	21.0	23.5	28.5	30.5	34.5	38.5	42.5	45.0	47.5	8.0

Table 9

Thermocouple Data for Re=41,500 Run

Radial Position (in)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	NOISE
$\sqrt{e'^2}$ (Milli- volts)	15.0	15.7	18.3	21.5	25.0	28.5	32.0	35.5	38.0	39.5	6.0

Table 10

Thermocouple Data for Re=49,800 Run

Radial Position (in)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	NOISE
$\sqrt{e'^2}$ (Milli- volts)	12.0	12.8	14.8	17.5	20.5	24.0	27.0	30.0	32.0	33.2	3.0



Table 11

Non-Isothermal Hot-Wire "Before" Calibration Data

$R_w - \bar{R}_a$ (Ohm) $\Delta P$ (in)* $\rightarrow$ $\downarrow$	2.20	1.620	1.330	0.932	0.480
1.00	1.865	1.820	1.795	1.740	1.665
1.20	1.990	1.940	1.915	1.850	1.775
1.40	2.125	2.070	2.045	1.955	1.875
1.60	2.230	2.175	2.145	2.080	1.960
1.80	2.325	2.265	2.235	2.180	2.075
2.00	2.410	2.355	2.320	2.265	2.150
2.20	2.500	2.435	2.400	2.340	2.225
2.40	2.575	2.515	2.475	2.410	2.295
2.60	2.650	2.590	2.550	2.490	2.360
2.80	2.725	2.660	2.620	2.555	2.425
3.00	2.790	2.725	2.680	2.620	2.485
3.20	2.855	2.785	2.745	2.686	2.585
3.40	2.920	2.845	2.805	2.746	2.640

\* Orifice Meter Manometer Fluid SPG 2.95



Table 12.

Cold Resistances in "Before" Calibration

P (in.)*	R <sub>cold</sub> (OHM)
2.120	7.42
1.620	7.46
1.330	7.49
0.932	7.57
0.480	7.80



Table 13

Temperature Difference Between Wall and Centerline

$\Delta P$ (in)*	$T_{r/R=1} - T_{r/R=0}$ °F
2.120	46
1.620	51
1.330	54
.932	61
.480	74

\*Orifice Meter Manometer Fluid SPG 2.95





Table 14

Non-Isothermal Hot-Wire RMS Voltage  
Fluctuation Data for  $r/R=0$

$R_w - \bar{E}_a$ (Ohm) ↓	$\Delta P$ (in)*→	2.120	1.620	1.330	0.932	0.480
1.00	24.8	Milli- volts	27.0	28.8	31.6	38.3
1.20	24.8		26.9	28.4	31.0	37.2
1.40	24.7		26.3	28.2	30.3	36.2
1.60	24.5		26.0	27.9	29.8	35.3
1.80	24.3		25.7	27.4	29.2	34.3
2.00	24.3		25.5	26.9	28.9	33.6
2.20	24.2		25.2	26.7	28.5	32.9
2.40	24.1		25.0	26.4	28.1	32.0
2.60	24.1		24.9	26.2	27.7	31.4
2.80	24.0		24.7	25.9	27.5	31.0
3.00	24.0		24.5	25.8	27.2	30.6
3.20	23.9		24.5	25.6	27.0	30.0
3.40	23.9		24.4	25.5	26.7	29.8

\* Orifice Meter Manometer Fluid SPG 2.95



Table 15

Non-Isothermal Hot-Wire RMS Voltage  
Fluctuation Data for  $r/R=.5$

$R_w - \bar{R}_a$ (Ohm)	$\Delta P(\text{in})^* \rightarrow$					
	2.120	1.620	1.330	0.932	0.480	
	Milli-					
1.00	42.9	volts 45.0	46.8	50.5	59.7	
1.20	42.9	44.8	46.8	50.0	58.3	
1.40	42.6	44.6	46.2	49.2	57.1	
1.60	42.6	44.0	45.8	48.7	56.2	
1.80	42.7	44.0	45.6	48.0	55.0	
2.00	42.7	43.8	45.1	47.5	54.2	
2.20	42.3	43.5	44.9	47.0	52.8	
2.40	42.3	43.3	44.8	46.2	52.2	
2.60	42.2	43.2	44.5	46.0	51.7	
2.80	42.8	43.2	44.5	45.8	50.8	
3.00	42.6	43.0	44.3	45.2	50.3	
3.20	42.6	43.0	44.3	45.1	49.5	
3.40	42.6	43.0	44.0	44.8	49.2	

\* Orifice Meter Manometer Fluid SPG 2.95



Table 16

Non-Isothermal Hot-Wire "After" Calibration Data

$\frac{\Delta P}{R_w - \bar{R}_a}$ (in)* $\rightarrow$ (Ohm)	2.120	1.620	1.330	0.932	0.480
1.00	2.010 (Volts)	1.945	1.920	1.860	1.775
1.20	2.140	2.100	2.070	1.985	1.890
1.40	2.235	2.215	2.180	2.120	2.000
1.60	2.365	2.320	2.285	2.220	2.125
1.80	2.470	2.420	2.385	2.320	2.215
2.00	2.565	2.515	2.480	2.405	2.295
2.20	2.655	2.600	2.565	2.495	2.375
2.40	2.740	2.685	2.645	2.570	2.450
2.60	2.820	2.765	2.720	2.645	2.525
2.80	2.900	2.840	2.795	2.720	2.595
3.00	2.970	2.915	2.860	2.785	2.655
3.20	3.070	2.980	2.930	2.845	2.715
3.40	3.135	3.075	2.995	2.910	2.775

\* Orifice Meter Manometer Fluid SPG 2.95



Table 17

Cold Resistances in "After" Calibration

P (in.)*	R <sub>cold</sub> (OHM)
2.120	7.21
1.620	7.24
1.330	7.26
0.932	7.29
0.480	7.43





## APPENDIX B



## APPENDIX B

## ORIFICE METER CALIBRATION

The orifice meter used was calibrated in place against a pitot tube located at the centerline of the test section. von Karman's universal velocity distribution<sup>18</sup> was used to calculate flow rates from the pitot tube velocity measurements. The calibration curve is shown in Figure 14. It is found as anticipated that a plot of flow rate versus the square root of the pressure drop is a straight line.<sup>19</sup>



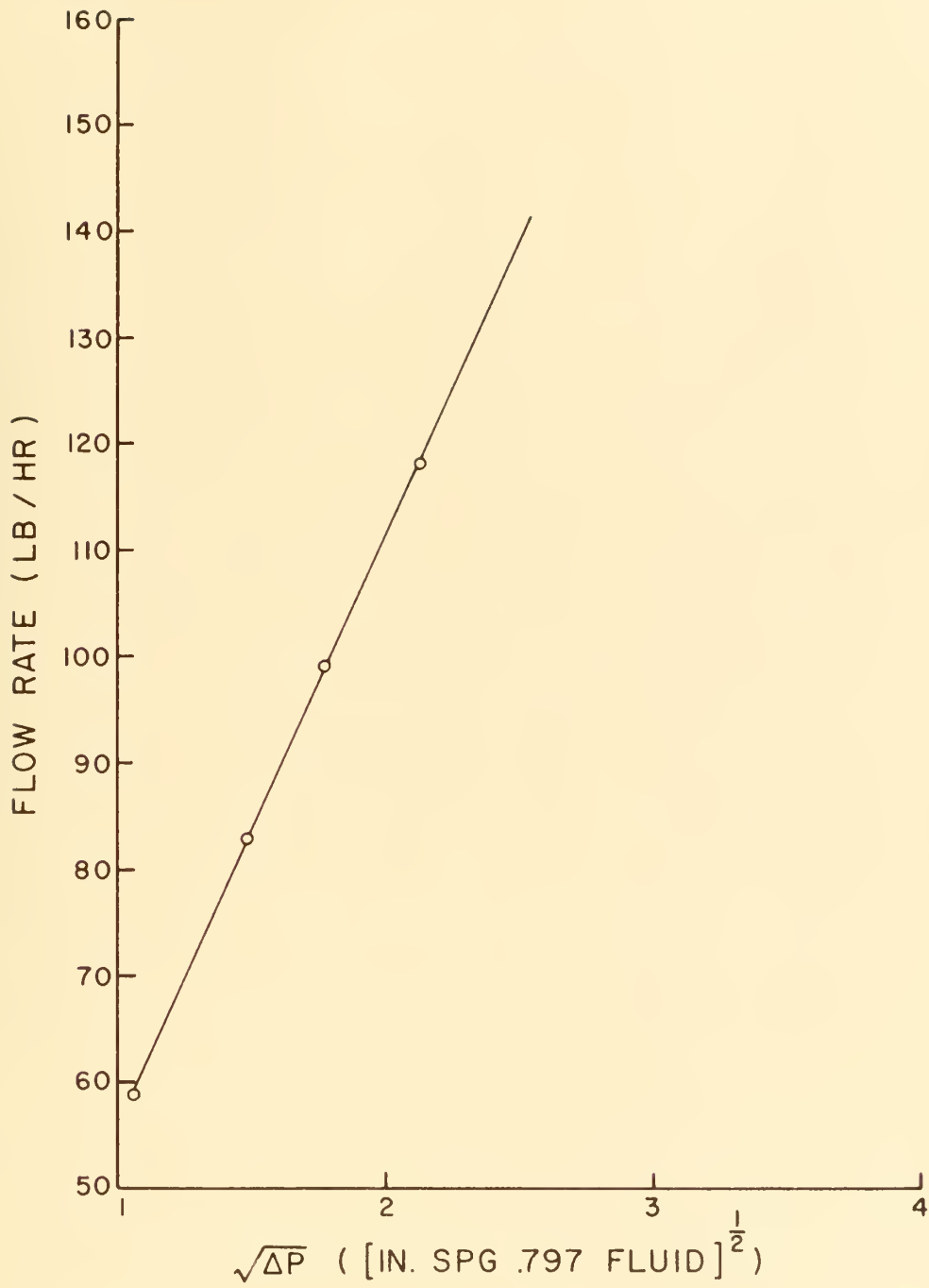


Figure 14. Orifice Meter Calibration Curve



APPENDIX C





## APPENDIX C

## AMPLIFIER FREQUENCY RESPONSE

The frequency response of the Tektronix amplifier is shown on the following page.



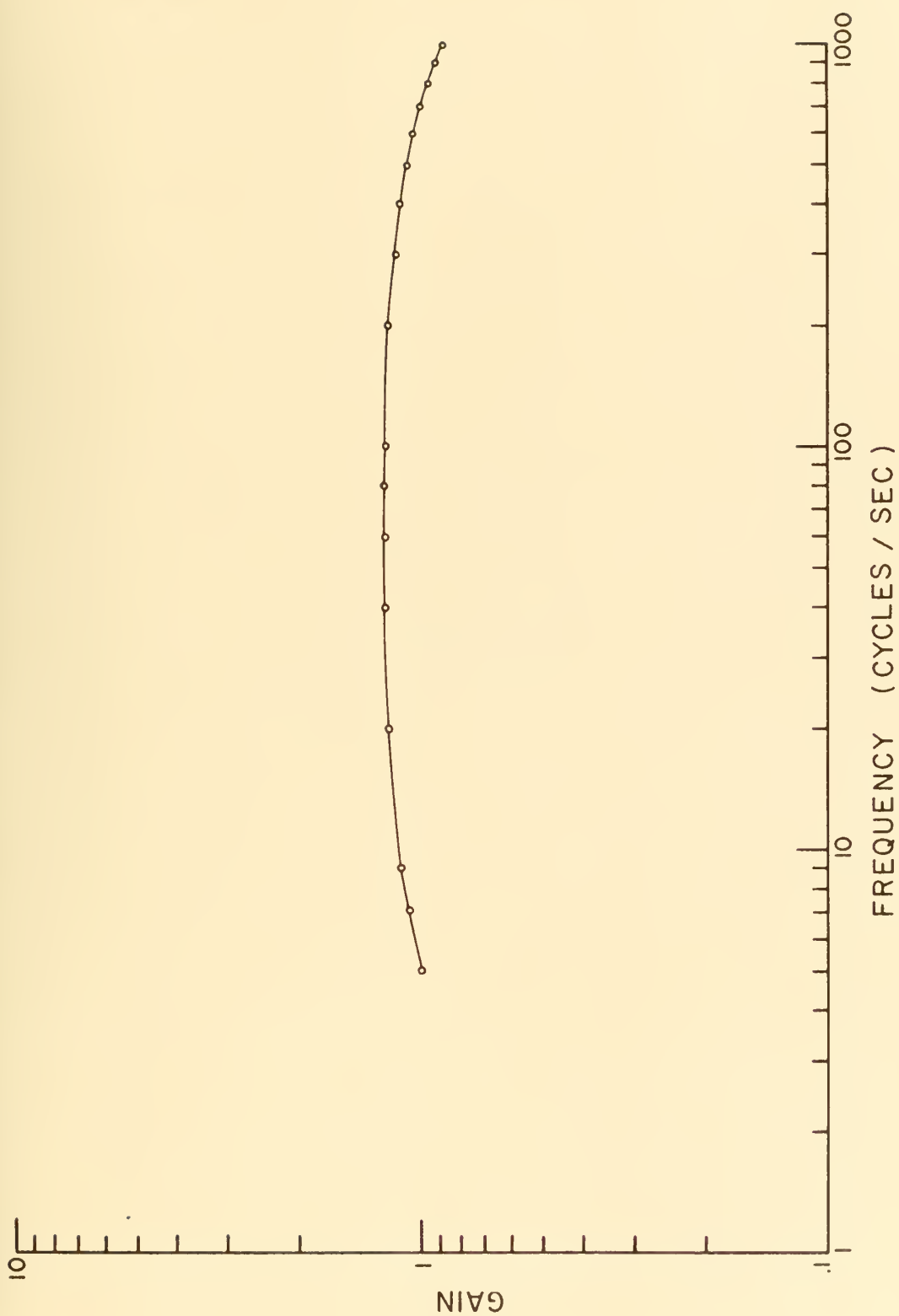


Figure 15. Amplifier Frequency Response



## APPENDIX D



## APPENDIX D

## RESISTANCE-TEMPERATURE CURVE FOR THE HOT-WIRE

Figure 16 shows the relationship between resistance and temperature for the hot wire used in the non-isothermal flow measurements. The dashed curve is the approximate relationship suggested by Kronauer.<sup>3</sup>







Figure 16. Resistance-Temperature Curve for Hot-Wire



APPENDIX E



## APPENDIX E

## CALIBRATION OF HOT-WIRE IN ISOTHERMAL FLOW

The isothermal flow data were taken on two different days. The set of data for a Reynolds Number of 49,800 was taken on the first day. The calibration curve for these data is shown in Figure 17. The constant  $C$  in Equation 18, which is the slope of the line in Figure 17 is  $1.67 \times 10^{-2}$ .

The data at Reynolds Numbers of 30,700 and 41,500 were taken on the second day. The calibration curve for these data is shown in Figure 18. The constant  $C$  for these data is  $1.69 \times 10^{-2}$ .

The value of  $C$  calculated from Equation 17 is  $0.84 \times 10^{-2}$ . The discrepancy between this value and that obtained from calibration is due to wire history effects in  $\alpha$  and  $R_0$  and the error inherent in King's potential flow value for  $B$ .



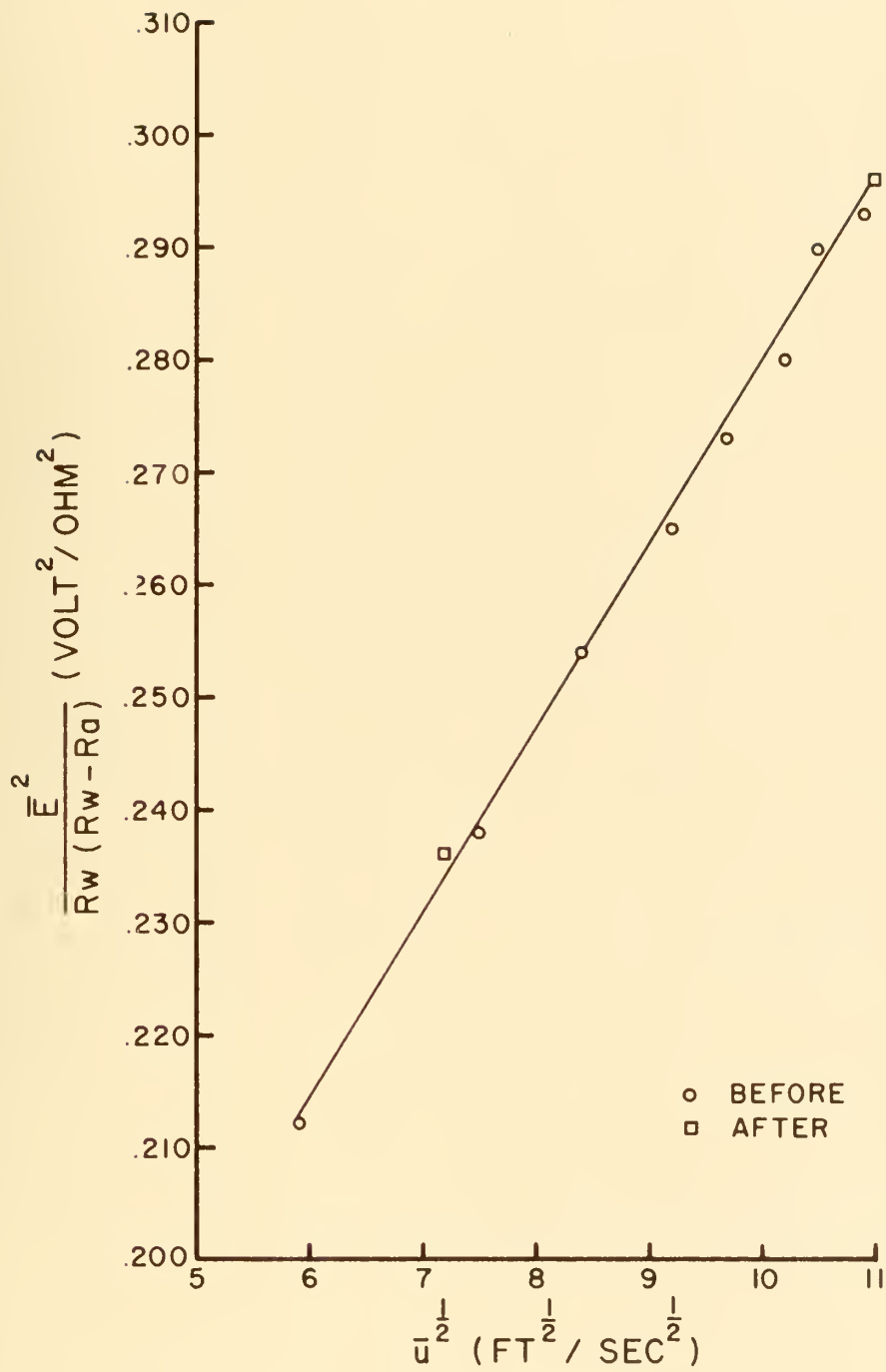


Figure 17. Isothermal Calibration of Hot-Wire I





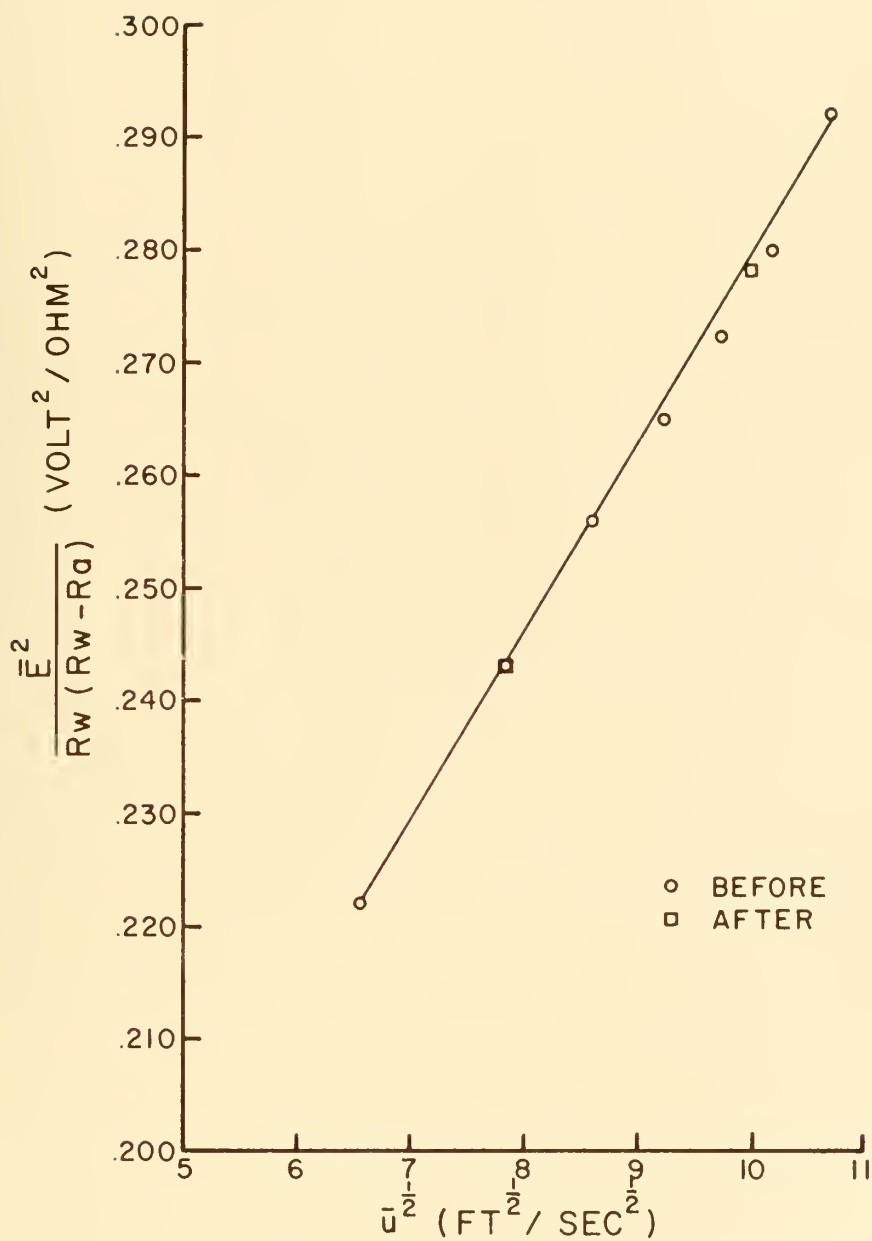


Figure 18. Isothermal Calibration of Hot-Wire II



APPENDIX F



## APPENDIX F

## LISTING OF CURVE FITTING PROGRAM

The computer subroutine used to perform least square curve fitting calculations is listed on the following pages.



```

SUBROUTINE POLYF1 (X, T, N, K0R, C, (D, A, N001)
C
C      DIMENSION FOR ARGUMENTS
000011 DIMENSION X(15),Y(15),A(225),C(15)
C
C      DIMENSION FOR SELF-GENERATED VALUES
000011 DIMENSION SUMA(50),SMTX(50),AMEA(50)
000011 PIS=0
000012 K10R=2*K0R
C
C      INITIALIZATION
000014 DO 1 I=1,K0R
000015   SMTX(I)=0.0
000017   1 AMEA(I)=0.0
000022   DO 2 I=1,K10R
000023     2 SUMA(I)=0.0
000027     SMTX=0.0
C
C      NORMALIZATION WITH RESPECT TO AMAX
000027   AMAX=A(1)
000031   DO 100 I=2,N
000033     IF (A(I) > AMAX) 100,101,101
000036   101 AMAX=A(I)
000041   100 CONTINUE
000044   DO 102 I=1,N
000045     102 A(I)=A(I)/AMAX
C
C
C      FORMULATION OF NORMAL EQUATIONS
000051   DO 3 J=1,K10R
000053     DO 3 I=1,N
000054       3 SUMX(J)=SUMX(J)+A(I)**J
000067     DO 4 I=1,N

```

```

POLY0010
POLY0020
POLY0040
POLY0050
POLY0070
POLY0090
POLY0100
POLY0110
POLY0120
POLY0130
POLY0140
POLY0150
POLY0160
POLY0170
POLY0180
POLY0190
POLY0200
POLY0210
POLY0220
POLY0230
POLY0240
POLY0250
POLY0260
POLY0270
POLY0280
POLY0290
POLY0300
POLY0310
POLY0320
POLY0330

```





```

000071 4 S=1=SUMY+Y(I)                                POLY0320
000075 6 SETAY=SUMY/PTS
000077 10 1=J=1,KOM
000100 6 SETAX(J)=SUMX(J)/PTS                                POLY0370
000104 10 1=K=1,N                                           POLY0380
000105 6 SETAX(J)=SETAX(J)+I(I)*X(I)*0.1                POLY0390
000122 10 1=K=1,KOM                                         POLY0400
000123 6 (I)=SETX(I)-PTS*AMEATX(I)*AMEANY              POLY0410
000132 10 1=J=1,KOM                                         POLY0420
000133 K=1+J                                               POLY0430
000134 1J=(J-1)*KOM+1                                       POLY0440
000137 6 A(IJ)=SUMX(K)-PTS*AMEATX(I)*AMEANX(J)         POLY0450
C
C (KOMP) 75 1=J=1,KOM                                     POLY0470
000155 11 1=(I-1)*KOM+1                                    POLY0480
000156 11 A(I11)=A(I11)/A(I)                               POLY0490
000161 10 12 J=2,KOM                                         POLY0500
000167 K=J-1                                                POLY0510
000170 10 14 1=J,KOM                                         POLY0520
000172 6 P1=0.0                                              POLY0530
000173 00114 K=1,KOM                                         POLY0540
000174 1K=(K-1)*KOM+1                                       POLY0550
000176 KJ=(J-1)*KOM+K                                       POLY0560
000201 114 AP1=AP1+A(IK)*A(KJ)                             POLY0570
000215 1J=(J-1)*KOM+1                                       POLY0580
000220 14 A(IJ)=A(IJ)-AP1                                   POLY0590
000226 JF=J+1                                               POLY0600
000227 1F(JF-KOM) 444, 444, 444                          POLY0610
000232 444 00 1K 1=J,KOM                                     POLY0620
000234 6 P1=0.0                                              POLY0630
000235 00116 K=1,KOM                                         POLY0640
000237 JK=(K-1)*KOM+J                                       POLY0650
000242 K1=(I-1)*KOM+K                                       POLY0660
000245 116 AP1=AP1+A(JK)*A(K1)                             POLY0670
000256 J1=(I-1)*KOM+J                                       POLY0680
000261 JJ=(J-1)*KOM+J                                       POLY0690
000264 16 A(J1)=(A(J1)-AP1)/A(JJ)                         POLY0700
000274 445 0000MY=0.0                                        POLY0710
000275 12 001100E                                           POLY0720
000300 C(I)=C(I)/A(I)                                       POLY0730
000302 10 18 1=2,KOM                                         POLY0740
000304 6 P1=0.0                                              POLY0750
000305 10=1-1                                               POLY0760
000307 10 11K K=1,1F                                         POLY0770
000310 1K=(K-1)*KOM+1                                       POLY0780
000313 11K AP1=AP1+A(1K)*C(K)                              POLY0790
000324 11 1=(I-1)*KOM+1                                       POLY0800
000327 18 C(I)=(C(I)-AP1)/A(11)                            POLY0810
000336 KOMM=KOM-1                                           POLY0820
000337 1F (KOMM) 122, 123, 122                             POLY0830
000340 122 00 21 1=1,KOMM                                     POLY0840
000342 6 P1=0.0                                              POLY0850
000343 K=K(P-1)                                              POLY0860
000344 KP=K+1                                                POLY0870
000346 00 121 K=KP,KOM                                         POLY0880
000347 KK=(K-1)*KOM+K                                       POLY0890
000352 121 AP1=AP1+A(MK)*C(K)                              POLY0900
000362 21 C(M)=C(M)-AP1                                    POLY0910
000367 123 AP1=0.0                                          POLY0920

```



```

000370      DO 24 I=1,KOR                      POLY0940
000372      24 AP1 =AP1 +AMFANX(I) *C(I)      POLY0940
000400      CO = AMFANY -AP1                  POLY0940
C                                           POLY0970
C      PERFORMALIZATION WITH RESPECT TO XMAX  POLY0990
000401      777 DO 774 I = 1,KOR             POLY1000
000403      774 C(I) = C(I)/XMAX**I        POLY1010
C                                           POLY1130
000413      DO 35 I=1,N
000414      35 X(I)=X(I)*XMAX
000420      778 SRES=0.0
000421      DO 877 I=1,N
000423      SMOOTH=C0
000424      DO 27 J=1,KOR
000426      27 SMOOTH=SMOOTH+C(J)*X(I)**J
000440      RES=Y(I)-SMOOTH
000442      SRES=SRES+RES**2
000444      877 CONTINUE
000447      STOV=SQRT(SRES/PTS)
000452      IF(NCUT.EQ.0) RETURN
000455      36 WHILE (0.24)
000461      29 FORMAT (50H          X          Y          SMOOTH      POLY1050
1      RES          )                      POLY1060
000461      DO 77 I=1,N
000466      SMOOTH=C0
000467      DO 37 J=1,KOR
000471      37 SMOOTH=SMOOTH+C(J)*X(I)**J
000503      RES=Y(I)-SMOOTH
000506      30 FORMAT (4F15.4)                POLY1160
000506      77 WHILE (0.30) X(I),Y(I),SMOOTH,RES
000537      WHILE (0.31) STOV
000544      31 FORMAT (10H0STOV      =F20.5)    POLY1200
000544      WHILE (0.33) CO
000556      33 FORMAT(10H0CO      =E20.10)
000556      WHILE (0.32) (C(I), I=1,KOR)
000601      32 FORMAT(10H0C(I)      /(5F20.10/))
000601      RETURN
000602      END

```

UNUSED COMPILER SPACE

001200



APPENDIX G



## APPENDIX G

## CALIBRATION OF HOT-WIRE IN NON-ISOTHERMAL FLOW

Figures 19 through 23 represent the calibration data used to compute the results presented for non-isothermal flow. The curves drawn through the data represent the least squares fit of parabolas to the data. These parabolas were differentiated analytically to obtain the values of  $S_u$  and  $S_T$  presented in Figures 9 and 10.

Figures 24 through 26 show calibration curves for representative values of  $\bar{u}$  and  $T_w - \bar{T}_a$  before and after fluctuation measurements were made. Table 18 gives a complete tabulation of  $S_u$  and  $S_T$  as functions of  $\bar{u}$  and  $T_w - \bar{T}_a$  before and after the fluctuation measurements.





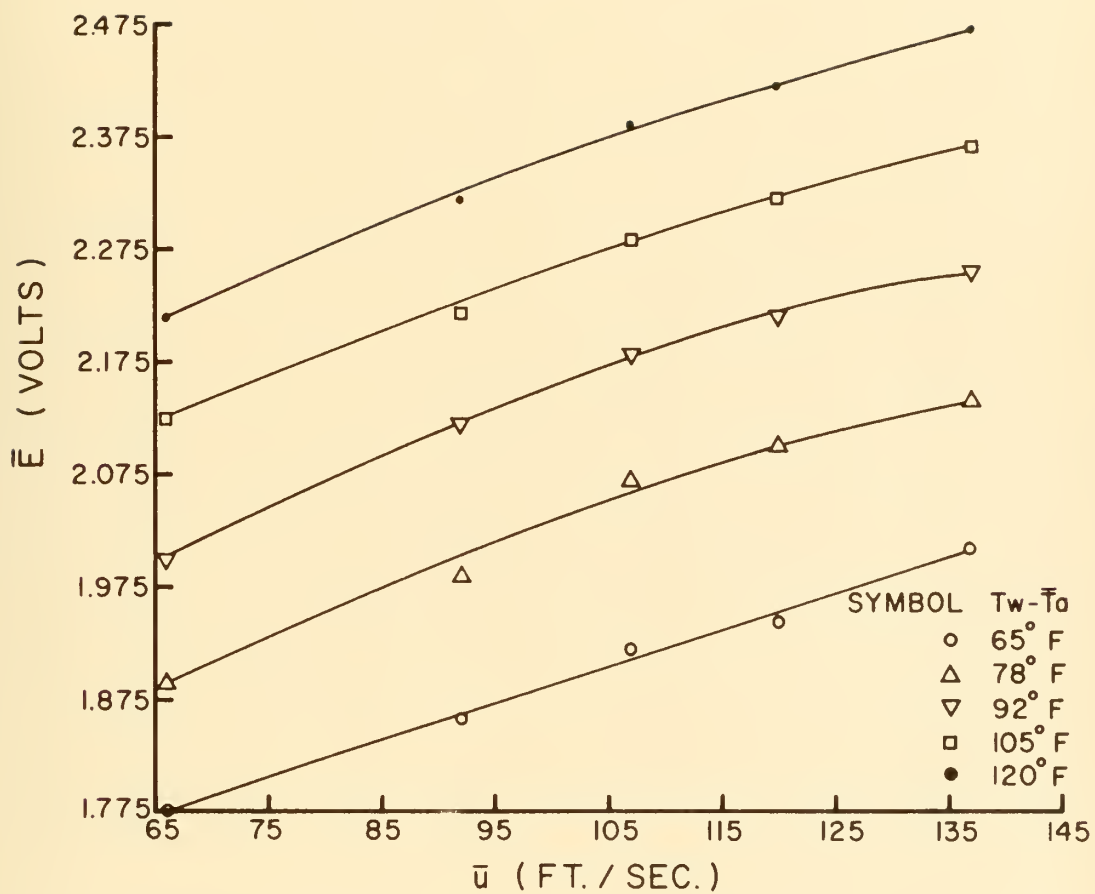


Figure 19. Non-Isothermal Calibration of Hot-Wire I



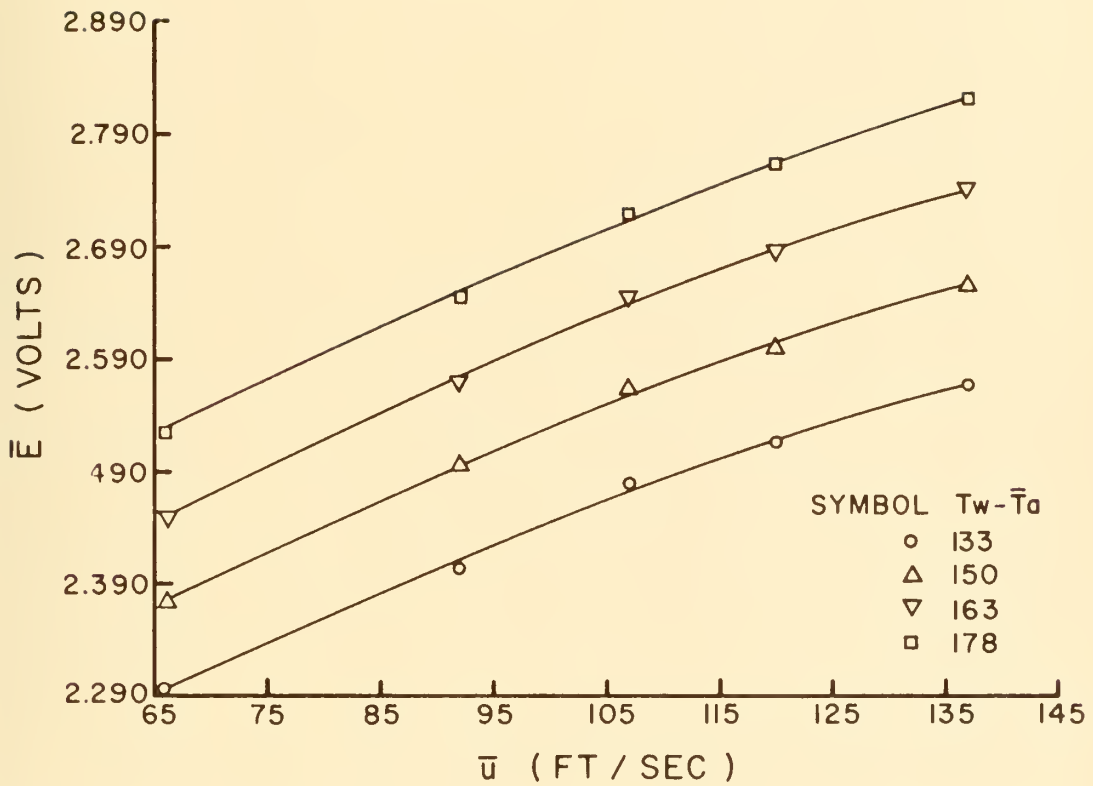


Figure 20. Non-Isothermal Calibration of Hot-Wire II



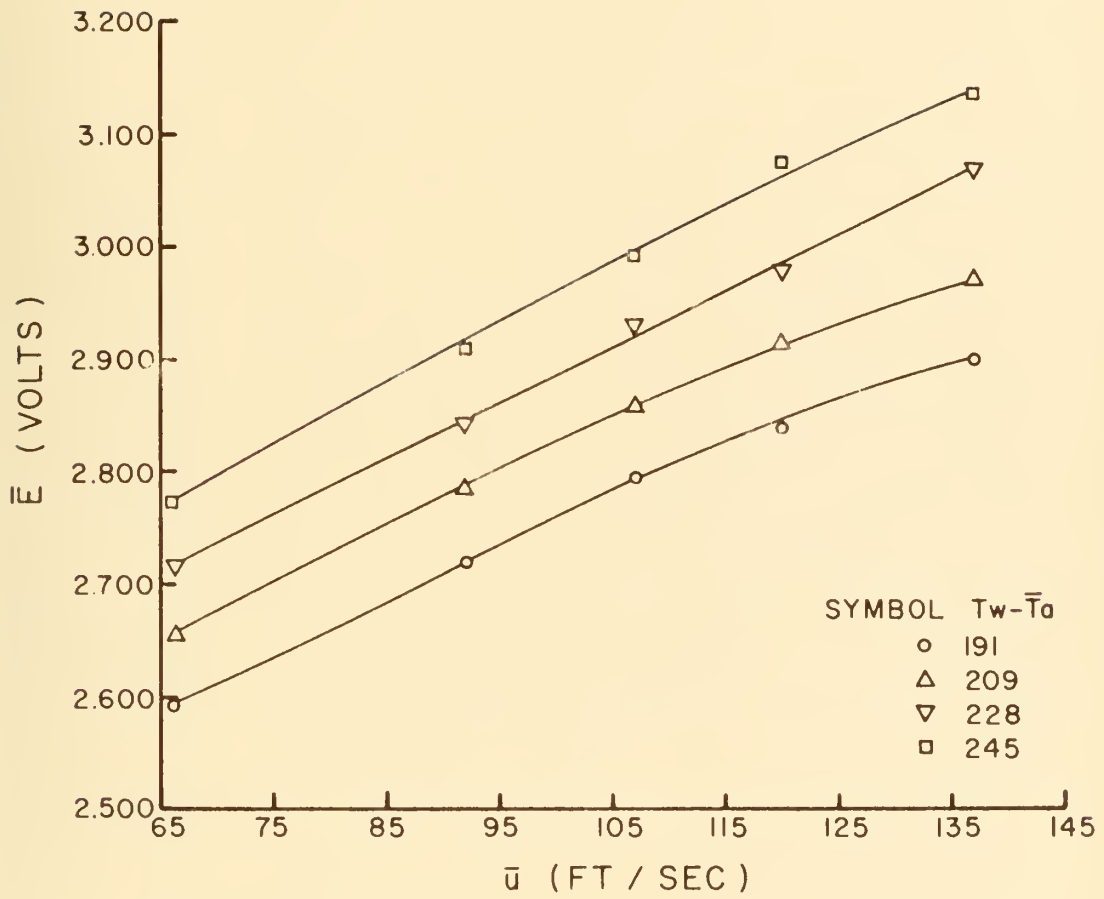


Figure 21. Non-Isothermal Calibration of Hot-Wire III



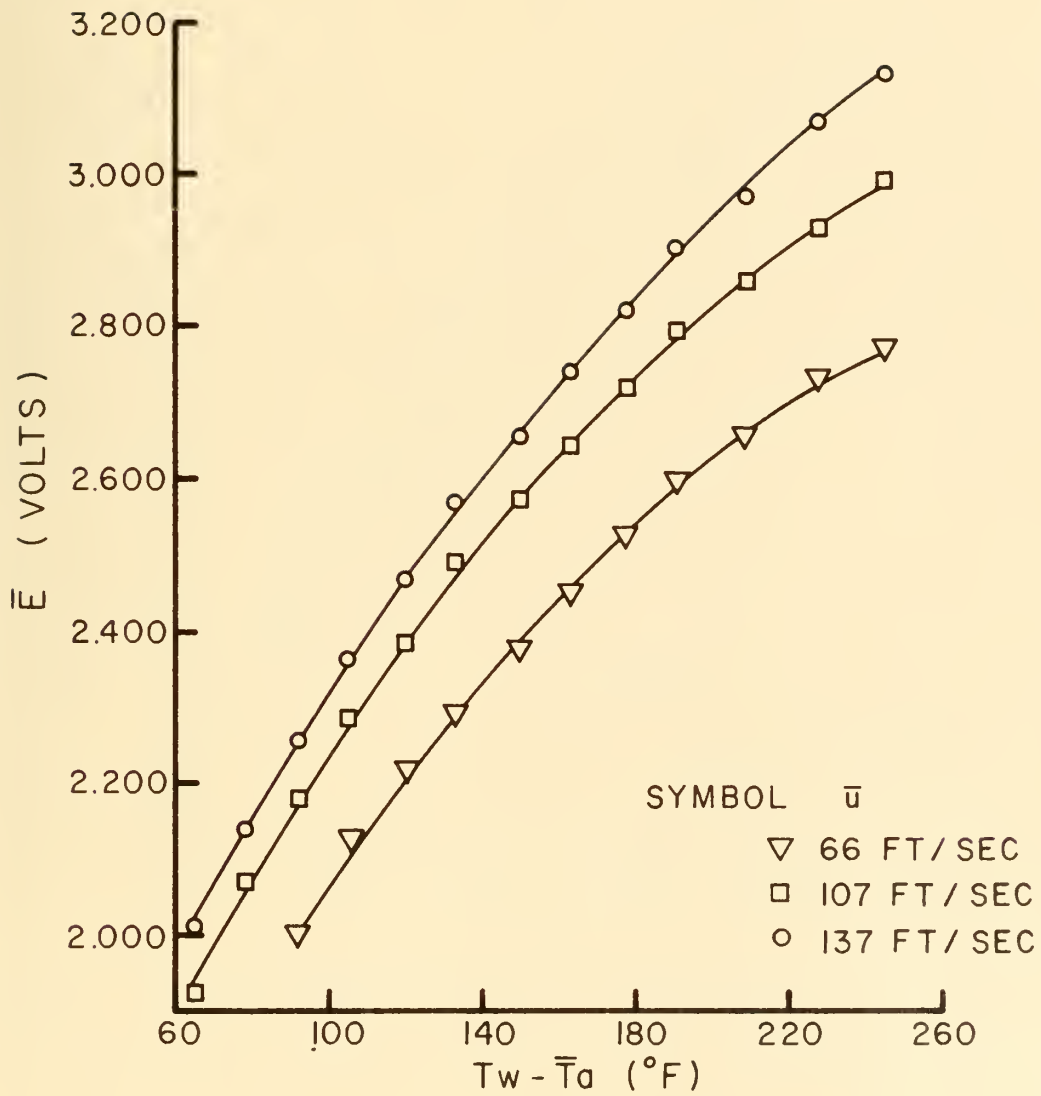


Figure 22. Non-Isothermal Calibration of Hot-Wire IV





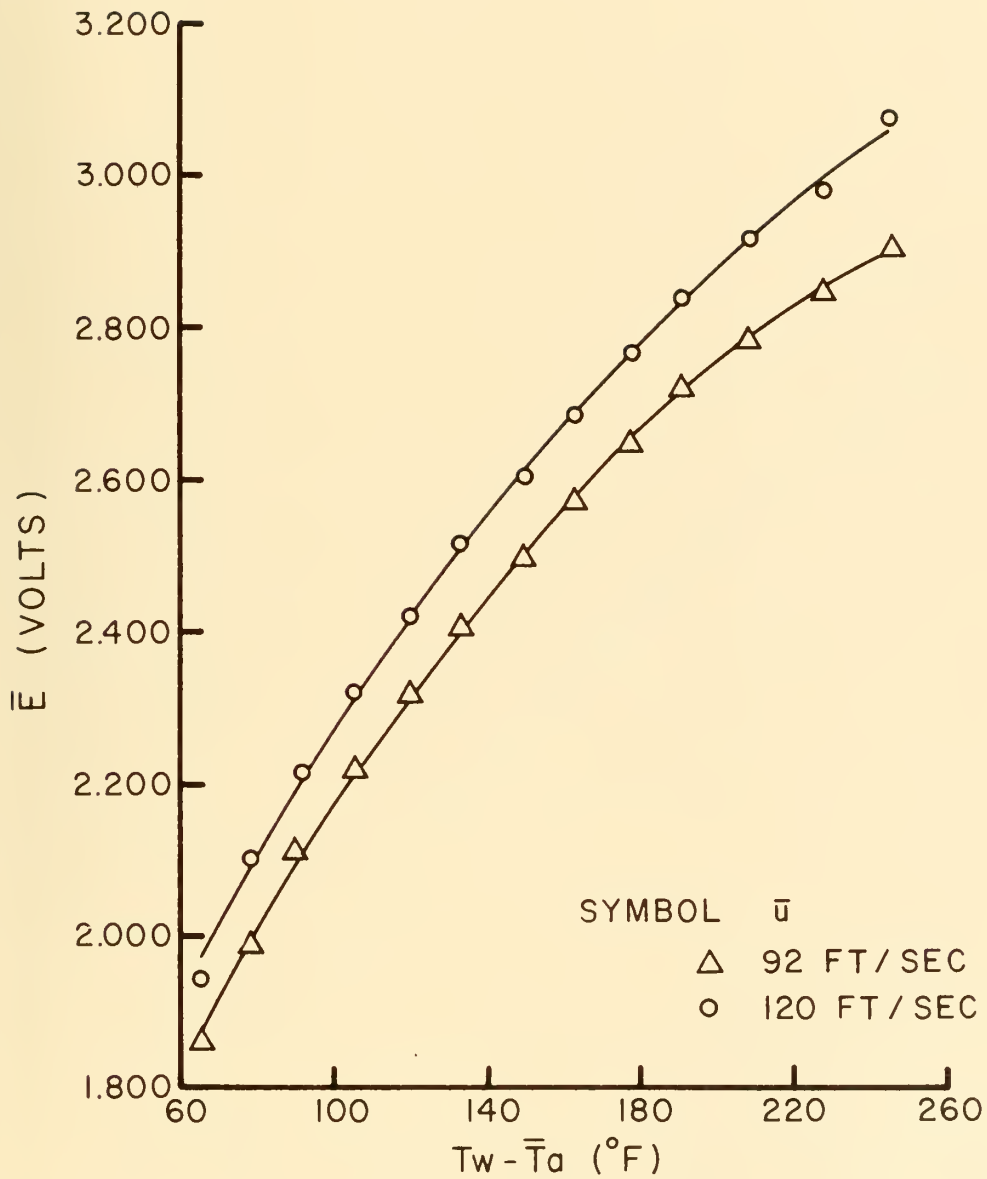


Figure 23. Non-Isothermal Calibration of Hot-Wire V



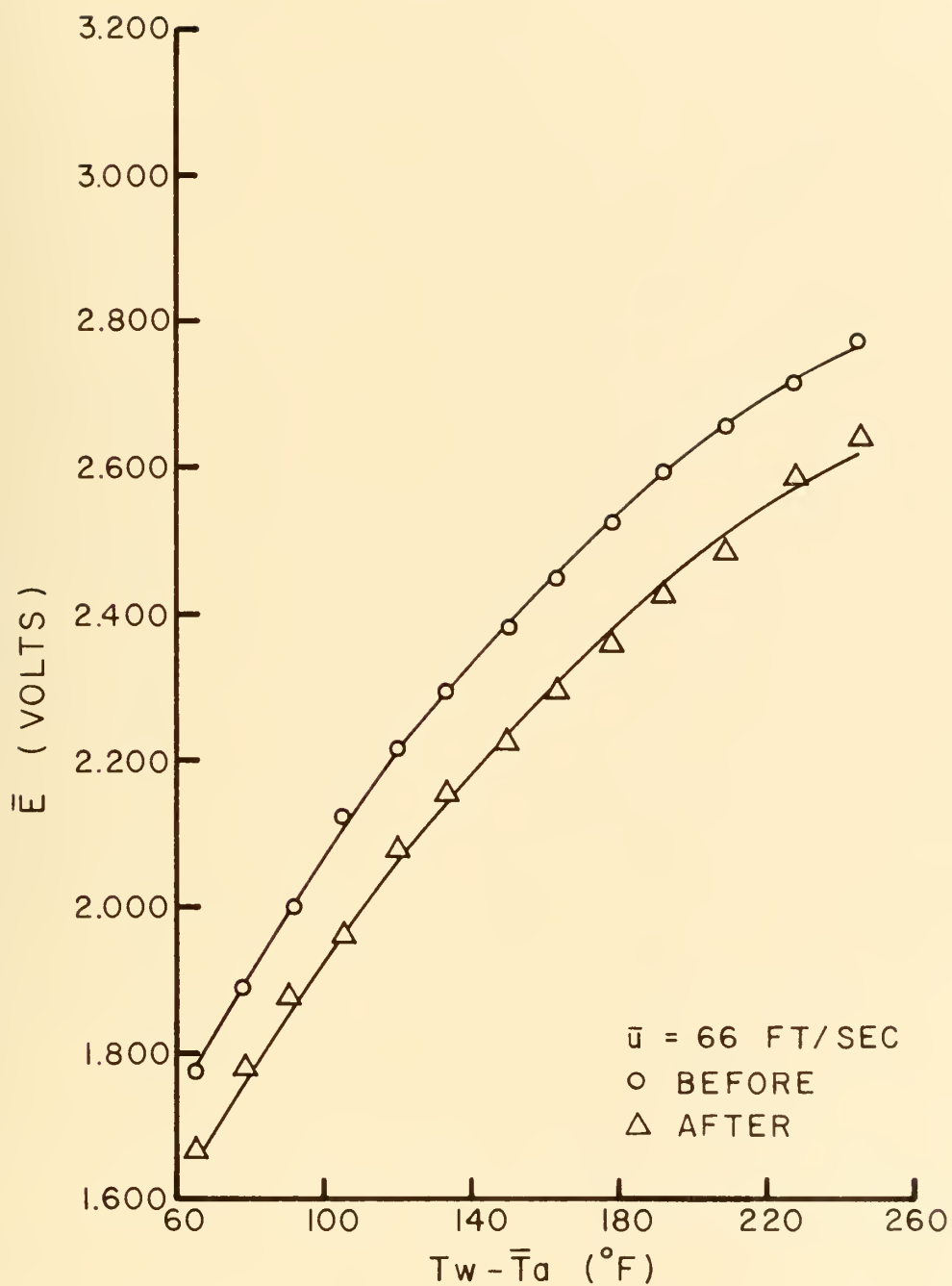


Figure 24. Calibration Drift I



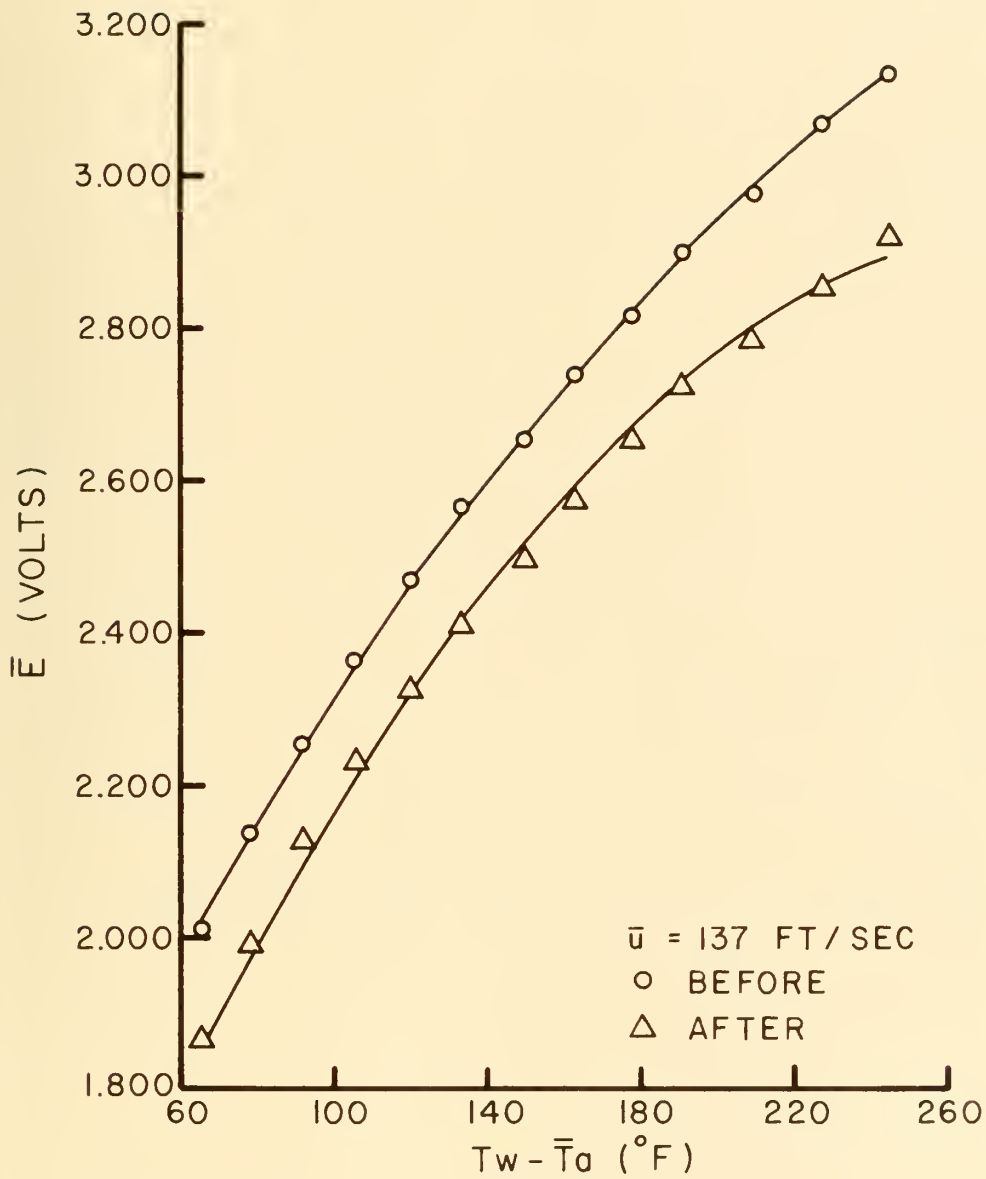


Figure 25. Calibration Drift II



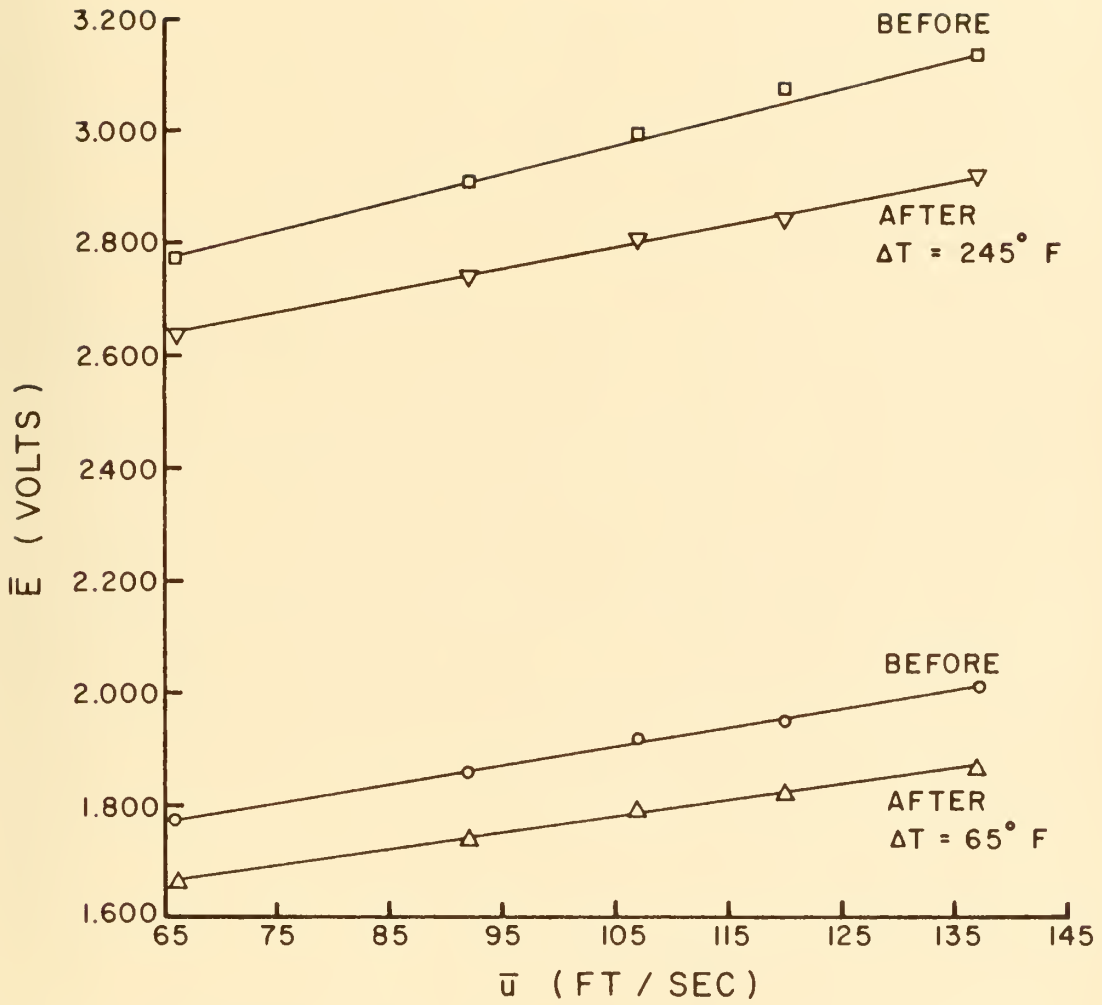


Figure 26. Calibration Drift III





Table 18

Values of  $S_u$  and  $S_T$  for Successive Calibrations

$T_w - \bar{T}_a$ $^{\circ}\text{F}$	$\bar{u}$ (Ft/Sec)											
	66		92		107		120		137			
	$S_u$	$S_T$	$S_u$	$S_T$	$S_u$	$S_T$	$S_u$	$S_T$	$S_u$	$S_T$	$S_u$	$S_T$
65	3.39 3.48	8.5 8.2	3.31 3.16	8.9 9.1	3.25 2.97	8.9 9.3	3.21 2.82	8.9 9.5	3.15 2.61	8.8 9.7		
78	4.87 3.61	8.1 7.8	3.96 3.38	8.5 8.6	3.44 3.25	8.5 8.8	2.98 3.15	8.5 8.9	2.39 3.03	8.4 9.2		
92	5.34 4.29	7.6 7.4	4.07 4.00	8.0 8.0	3.33 3.82	8.0 8.2	2.68 3.68	8.1 8.3	1.85 3.48	8.0 8.6		
105	4.30 5.46	7.1 6.9	3.66 4.42	7.5 7.4	3.29 3.78	7.5 7.6	2.97 3.30	7.6 7.7	2.55 2.61	7.6 7.9		
120	4.61 4.45	6.6 6.5	3.88 3.93	7.0 6.9	3.45 3.60	7.0 7.0	3.08 3.36	7.1 7.1	2.60 3.02	7.2 7.3		
133	5.70 4.99	6.2 6.1	5.08 4.20	6.5 6.4	4.72 3.70	6.6 6.5	4.41 3.34	6.7 6.6	4.01 2.80	6.8 6.7		
150	5.25 4.87	5.6 5.5	4.29 4.32	5.9 5.8	3.74 3.97	6.0 5.8	3.27 3.71	6.2 5.9	2.64 3.34	6.3 6.0		
163	5.33 5.09	5.1 5.1	4.44 4.47	5.4 5.2	3.92 4.08	5.5 5.2	3.47 3.80	5.8 5.3	2.89 3.39	5.9 5.4		
178	5.31 5.63	4.6 4.6	4.49 4.70	4.9 4.7	4.02 4.11	5.0 4.6	3.61 3.67	5.3 4.7	3.08 3.05	5.5 4.8		



Table 16 (cont'd.)

191	5.41	4.1	4.61	4.4	4.14	4.5	3.74	4.9	3.21	5.1
	5.64	4.2	4.81	4.1	4.29	4.0	3.91	4.0	3.36	4.1
209	5.68	3.5	4.81	3.7	4.30	3.9	3.86	4.3	3.29	4.5
	5.72	3.7	4.88	3.5	4.35	3.4	3.96	3.4	3.40	3.4
228	5.18	2.8	5.03	3.0	4.94	3.2	4.87	3.7	4.77	4.0
	3.96	3.1	4.05	2.8	4.11	2.7	4.15	2.7	4.21	2.7
245	5.88	2.3	5.38	2.4	5.08	2.7	4.83	3.1	4.50	3.5
	4.07	2.6	4.18	2.2	4.24	2.0	4.29	2.0	4.37	2.0

Before

After



APPENDIX H



APPENDIX H

KOVASZNAV FLUCTUATION DIAGRAMS

Figures 27 through 29 show the Kovasznav Fluctuation Diagrams for three representative cases.

The parabolas that fit these data are:

Figure	Parabola
27	$(\frac{\overline{e'^2}}{S_T^2} - \overline{t'^2}) = 2.64 + 16.9(\frac{S_u}{S_T}) + 19.1(\frac{S_u}{S_T})^2$
28	$(\frac{\overline{e'^2}}{S_T^2} - \overline{t'^2}) = 0.43 + 18.9(\frac{S_u}{S_T}) + 16.2(\frac{S_u}{S_T})^2$
29	$(\frac{\overline{e'^2}}{S_T^2} - \overline{t'^2}) = 0.21 + 42.6(\frac{S_u}{S_T}) + 47.3(\frac{S_u}{S_T})^2$

$\overline{u't'}$  is then found by dividing the coefficient of  $\frac{S_u}{S_T}$  by -2, and  $\sqrt{\overline{u'^2}}$  is the square root of the coefficient of  $(\frac{S_u}{S_T})^2$ . The results from the parabolas given above are listed in Table 19.

Table 19  
Sample Results for  $\sqrt{\overline{u'^2}}$  and  $\overline{u't'}$

Reynolds Number And r/R	$\sqrt{\overline{u'^2}}$	$\overline{u't'}$
27,400    0.0	4.36	-8.45
38,200    0.0	4.03	-9.45
38,200    0.5	6.89	-21.3





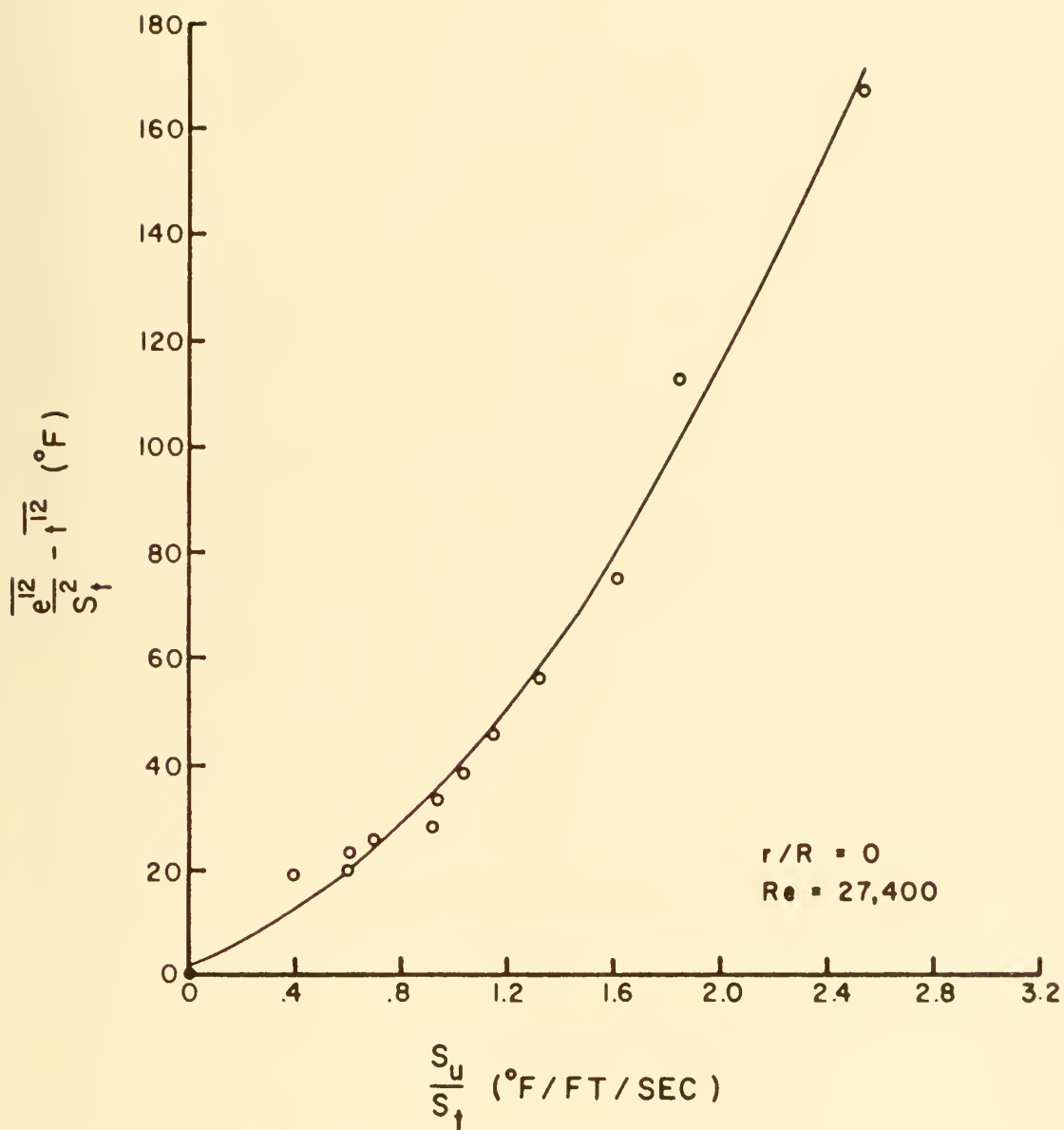


Figure 27. Kovasznay Fluctuation Diagram I



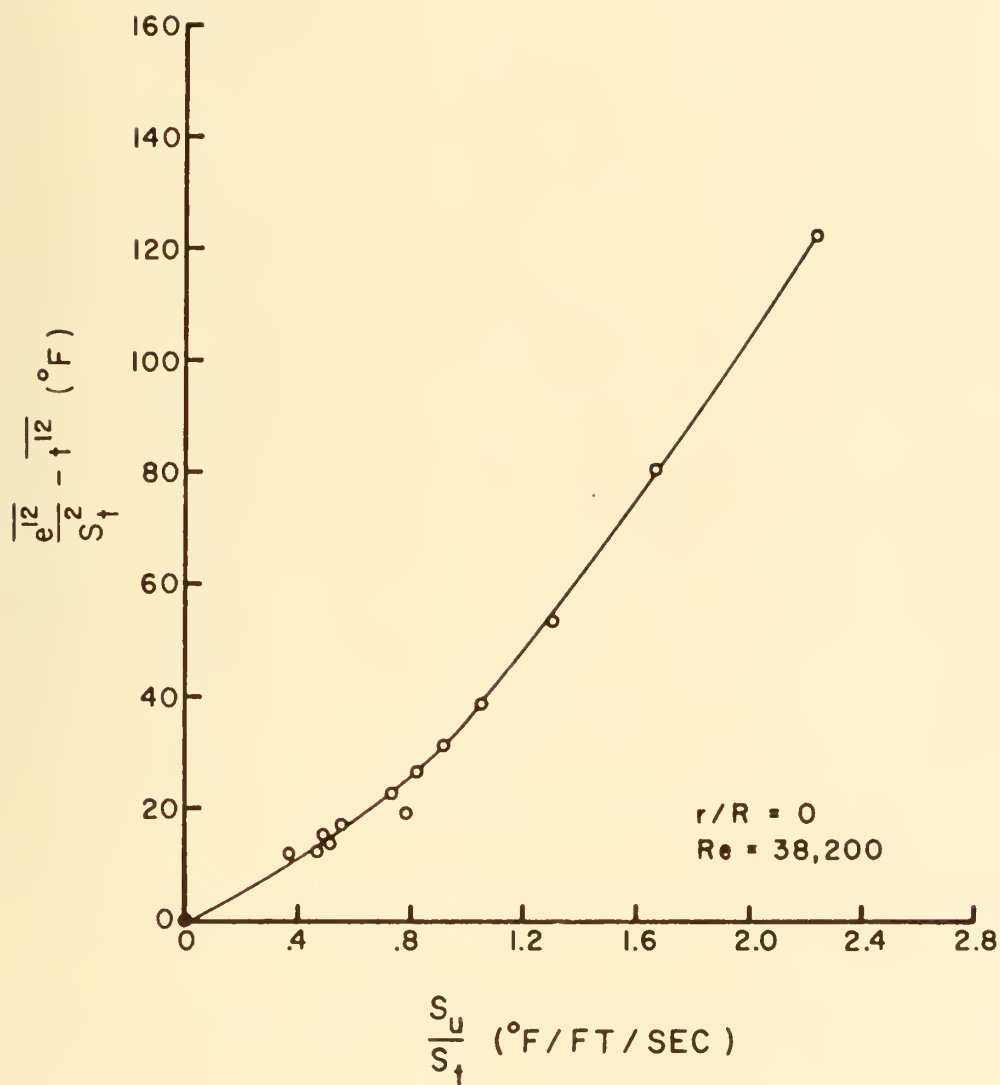


Figure 28. Kovasznay Fluctuation Diagram II



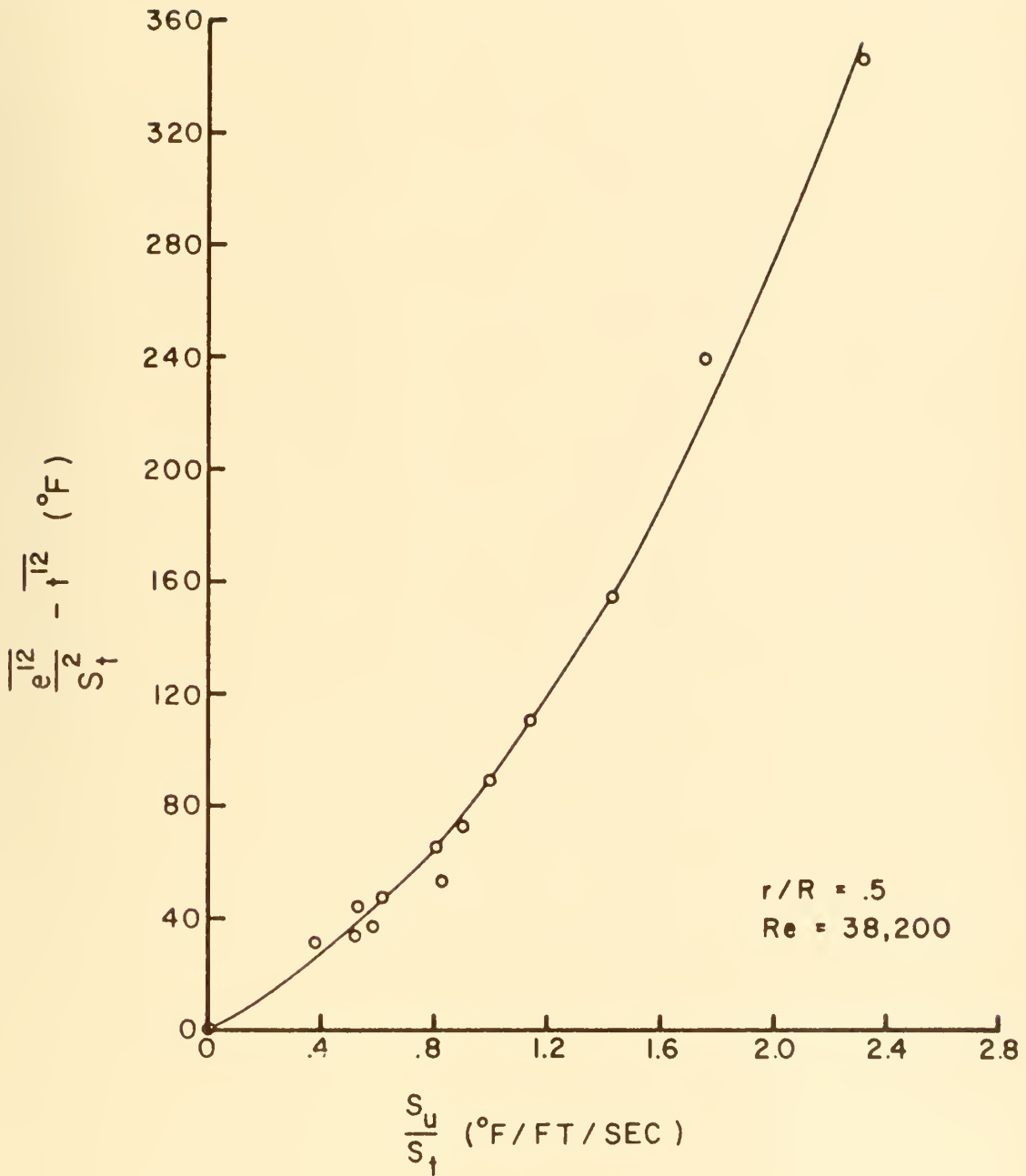


Figure 29. Kovaszny Fluctuation Diagram III



## APPENDIX I





## APPENDIX I

## ERROR ANALYSIS

The results of the isothermal flow measurements with the hot-wire deviate from the results of Sandborn<sup>11</sup> and Laufer<sup>10</sup> by less than 10 percent.

The results of a preliminary non-isothermal run duplicating the conditions of Rodriguez-Ramirez and using the rapid response thermocouple agreed with his results within 5 percent.

Since the errors in the results of the non-isothermal flow measurements with the hot-wire are quite large, a detailed estimate of their magnitude is needed.

It is assumed that the errors in  $\sqrt{u'^2}/\bar{u}_L$  and  $\overline{u't'}/\bar{u}_L (T_o - T_L)$  are primarily the result of errors in  $S_u$  and  $S_T$ . In order to obtain an estimate of the errors in  $S_u$  and  $S_T$ , an analysis was made of the discrepancies between successive calibrations as tabulated in Table 18.

Note that the actual errors in  $S_u$  and  $S_T$  come from a continuous drift in  $\bar{E}$  during a given calibration as outlined in the DISCUSSION section. Since it is not possible to measure this drift, recourse was made to analyzing by this method. Thus the error estimates obtained below do not represent confidence limits on the results but only rough approximations to the confidence limits. In Table 18, the largest



discrepancies occur for  $\bar{u} = 137$  ft/sec. The percentage error, based on the before value, between the before and after values, was determined for each entry in the 137 ft/sec column. All the  $S_T$  errors were summed and divided by the number of entries and likewise for  $S_u$ . Thus, average errors were determined to be 19 percent in  $S_u$  and 14 percent in  $S_T$ .

The propagation of these errors into the coordinates of the Kovasznay Fluctuation Diagram is as follows:

$$\frac{\Delta \left( \frac{\overline{e'^2}}{S_T} - \frac{\overline{t'^2}}{S_T} \right)}{\frac{\overline{e'^2}}{S_T} - \frac{\overline{t'^2}}{S_T}} = 2 \frac{\Delta S_T}{S_T} = 28 \text{ percent.}$$

$$\frac{\Delta \left( \frac{S_u}{S_T} \right)}{\frac{S_u}{S_T}} = \frac{\Delta S_u}{S_u} + \frac{\Delta S_T}{S_T} = 33 \text{ percent.}$$

These errors were assumed to apply to all values of  $\bar{u}$  and  $r/R$ .

The value of  $\frac{S_u}{S_T}$  for each point of the Kovasznay Fluctuation Diagram for  $\bar{u} = 66$  ft/sec  $r/R = 0$  was increased by 33 percent, and the value of  $\frac{\overline{e'^2}}{S_T} - \frac{\overline{t'^2}}{S_T}$  was decreased by 28 percent. A parabola was fitted

to the resulting points and  $\overline{u'^2}$  and  $\overline{u't'}$  determined. The new values differed from the original values by 72 percent and 100 percent respectively. Since

$$\Delta \frac{\sqrt{\overline{u'^2}}}{\overline{u'^2}} = \frac{1}{2} \Delta \frac{\overline{u'^2}}{\overline{u'^2}}$$



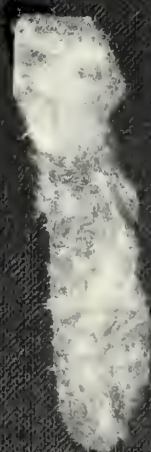
the error in  $\sqrt{\overline{u'^2}}$  is 36 percent. This 36 percent error was used as the limit of error for all values of  $\sqrt{\overline{u'^2}}/u_L$ , and 100 percent was used for all values of  $\overline{u't'}/\bar{u}_{cL}(T_o - T_L)$ .











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